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Results and Analysis of a Round-Robin Test Program for Liquid-Heating Flat-Plate Solar Collectors

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Preface

In discussing this round robin testing program, certain commercial components were used and are identified in order to provide a descriptive characterization of their features. Inclusion of a given component in this report in no case implies a recommendation or endorsement by the National Bureau of Standards, and the presentation should not be construed as a certification that any component would provide the indicated performance. Similarly, the omission of a component does not imply that its capabilities are less than those of the included components. This report is intended to be informative and instructive and not an evaluation of any commercially available components.

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Abstract

A round robin test program was conducted at 21 United States test facilities, using a common test procedure, to determine the intercomparability of thermal performance data pertaining to two liquid-heating flat-plate solar collectors.

The statistical analysis of the data revealed a relatively large spread in the measured values of collector efficiency. Data from approximately half the facilities were then selected for detailed analysis. A collector analytical model was used to show that less than one-third of the mean-square distance could be attributed to different environmental conditions from facility to facility. It was found that the data showed less scatter for one of the two collectors than for the other. In general, the data were consistent for any single facility; most of the scatter was therefore attributed to systematic uncertainties from facility to facility. When the data from six participants reportedly adhering to the requirements of ASHRAE Standard 93-77 were analyzed, the scatter was found to be within normal limits expected for the test procedure.

Key Words: Measurement; modelling; solar; standards; testing

1. Introduction

A proposed procedure for testing and rating solar collectors based on thermal performance was first published by the National Bureau of Standards (NBS) in 1974 [1-3]. The procedure prescribed that a series of outdoor steady-state tests be conducted to determine the near-normal-incidence efficiency of the collector over a range of collector operating temperature conditions. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has recently adopted ASHRAE Standard 93-77 [4], which is similar to the original NBS procedure but calls for additional tests to determine the collector time constant, as well as an incident angle correction factor that can be applied to the near-normal-incidence efficiency to determine collector performance as a function of incidence angle.

Since the publication of the NBS procedure [1], several testing loops have been built at the NBS site in Gaithersburg, Md. and experiments conducted to verify the applicability of the test procedure to a variety of commercially-available collectors. In addition, experiments have been conducted to support the development of the new tests which have been included as part of ASHRAE Standard 93-77. The results of these experiments will be forthcoming in a separate publication.

A second major part of the NBS solar collector test development work has consisted of the round robin testing program described in this report. The purpose of the program was to have a variety of testing laboratories across the United States attempt to utilize the test procedure and then determine the extent to which the results differed or were comparable.

2. Collector Performance

The performance of flat-plate collectors operating under steady-state conditions can be described by the following relationship [5]:

$$\frac{q_u}{A} = I(\tau\alpha)_e - U_L(\bar{t}_p - t_a) \qquad (1)$$

where q_u = useful heat output, W

A = cross-sectional area, m^2

I = total solar energy incident upon the plane of the collector per unit time per unit area, W/m^2

$(\tau\alpha)_e$ = effective transmittance-absorptance product for the cover plate-absorber combination

U_L = heat transfer loss coefficient for the solar collector, $W/(m^2 \cdot {}^\circ C)$

$\bar{t}_p$ = average temperature of the absorber surface of the solar collector, °C

t_a = ambient air temperature, °C

If one introduces the definition of either the collector efficiency factor F' or the collector heat removal factor F_R [6], equation (1) can be rewritten*

$$\frac{q_u}{A} = F'I(\tau\alpha)_e - F'U_L \left(\frac{t_{f,i} + t_{f,e}}{2} - t_a\right) \tag{2}$$

or

$$\frac{q_u}{A} = F_R I(\tau\alpha)_e - F_R U_L (t_{f,i} - t_a) \tag{3}$$

where $t_{f,e}$ = temperature of the heat transfer fluid leaving the collector, °C

$t_{f,i}$ = temperature of the heat transfer fluid entering the collector, °C

If the solar collector efficiency is defined by

$$\eta = \frac{q_u}{AI} \tag{4}$$

then the efficiency can be written as

$$\eta = (\tau\alpha)_e - U_L \frac{\bar{t}_p - t_a}{I} \tag{5}$$

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* Equation (2) is only approximately correct. The collector efficiency factor F' is defined in terms of the local fluid temperature and since the fluid temperature varies exponentially from inlet to exit, equation (2) is incorrect. The error is insignificant for flat-plate collectors using a liquid heat transfer fluid but can be significant for those using air.

or

$$\eta = F'(\tau\alpha)_e - F'U_L \frac{\frac{t_{f,i} + t_{f,e}}{2} - t_a}{I} \qquad (6)$$

or

$$\eta = F_R(\tau\alpha)_e - F_RU_L \frac{t_{f,i} - t_a}{I} \qquad (7)$$

Regardless of which form of the efficiency equation is used, equations (5-7) indicate that if the efficiency is plotted against some appropriate parameter ($\Delta t/I$), a straight line will result where the slope is some function of U_L and the y intercept is some function of $(\tau\alpha)_e$. In reality U_L is not a constant but rather a function of the operating temperature of the collector and of the ambient weather conditions such as air temperature, sky temperature, and wind velocity and direction. In addition, $(\tau\alpha)_e$ varies with incident angle to the collector and can vary to some extent as a function of the spectral and spatial distribution of the incoming solar radiation.

3. Collector Test Procedure

The procedure proposed by NBS in references 1 and 2 is based on collectors that can be isolated so that they have effectively one inlet and one outlet. The energy of the fluid entering and leaving the collector can be determined by making appropriate measurements. These quantities are then compared to the energy incident upon the collector (also determined by measurement) in order to calculate the collector efficiency. The fluid can be either a liquid or a gas but not a combination of the two.

As part of the procedure, the apparatus to be used is specified when the heat transfer fluid is a liquid (Figure 1) or air (Figure 2). The detailed requirements of the apparatus are given along with specifications for instrumentation to be used in measuring incident solar radiation, temperature, temperature difference, liquid flow rate, air flow rate, pressure, pressure drop, time and weight. For the specification of instrumentation, emphasis was placed on utilizing existing standards and other manuals of acceptable practice.

The series of tests consists of determining the average efficiency for 15-minute periods (integrating the energy quantities) over a range of temperature differences between the average fluid temperature and the ambient air. The efficiency is then calculated by

$$\eta = \frac{\int_0^{\tau} \dot{m}c_p \,(t_{f,e} - t_{f,i})\, d\tau}{A \int_0^{\tau} I \, d\tau} \qquad (8)$$

where

$\dot{m}$ = mass flow rate of the heat transfer fluid, kg/s

c_p = specific heat of the heat transfer fluid, J/(kg ·°C)

The flow rate is required to be steady and vary by less than $\pm$ 1.0 percent for the duration of each test. In addition, the heat transfer fluid shall have a known specific heat which varies by less than 0.5 percent over the temperature range of the fluid during a particular 15-minute test period. Consequently, the efficiency can be determined by

$$\eta = \frac{\dot{m}c_p \int_0^\tau (t_{f,e} - t_{f,i})\, d\tau}{A \int_0^\tau I\, d\tau} \qquad (9)$$

The test apparatuses specified in references 1 and 2 have been designed so that the temperature of the fluid entering the collector can be controlled to selected values. This feature is used to obtain the data over the temperature range desired. At least 16 data points are required for a complete test series and they must be symmetrical with respect to solar noon (to prevent biased results due to possible transient effects).

During each test period, the incident solar radiation must be "quasi-steady" as indicated in Figure 3 (in contrast to days in which cloud cover can cause a time distribution such as shown in Figure 4). Other requirements that must be satisfied for each data point are that the 15-minute average insolation be greater than 630 W/m^2 and the incident angle between the direct solar beam and the outward drawn normal from the collector be less than 45°. In addition, the range of ambient temperatures for the entire test series must be less than 30°C.

In developing the test procedure and writing the specific requirements, one main area of concern was ensuring that the measurements made would be sufficiently accurate so that the collector efficiency values would be meaningful.

It is recommended that the temperature rise in the heat transfer fluid passing through the solar collector be measured with either a thermopile (air or liquid as the transfer fluid) or calibrated resistance thermometers (only with a liquid). It is felt that an accuracy of ± 0.1°C is possible with such sensors and associated read-out devices. A variety of liquid flow meters are available that will enable $\dot{m}$ to be determined to within $\pm$ 1 percent of the measured value. The measurement of the incident solar radiation using pyranometers is perhaps the most critical and least accurate of all the measurements specified. As described in reference 2, typical accuracies of better than 5 percent are difficult to attain. However, Latimer has shown [7] that it is possible to obtain an accuracy of ± 2.3 percent with the better pyranometers provided they have been calibrated directly against a primary or a working standard pyrheliometer using the sun as a source and that they are properly installed and maintained. Based on this analysis, the test procedure should result in efficiency values accurate to within ± 4-5 percent.

As mentioned previously, ASHRAE has recently adopted Standard 93-77 which is similar to the NBS procedure. It was not adopted in time to be specified in this round robin test program; however, its main features will be described here for purposes of comparison.

The major changes in the conduct of the efficiency tests as specified in Standard 93-77 compared to that specified in the NBS procedures [1 and 2] are as follows:

1. The testing apparatus for water-cooled collectors has been modified to include a storage tank for damping out thermal transients and a by-pass for periodically calibrating the flow meter in place.

2. The testing apparatus for air heaters has been rearranged so that air is "pulled" through the collector instead of being blown through it (slight negative gage pressure in the collector).

3. More stringent requirements have been included for the measurement of solar radiation. Only pyranometers which meet or exceed the characteristics of a first class pyranometer as classified by the World Meteorological Organization [8] are allowed.

4. In conducting the test, data must be taken when the incident angle is less than 30° (compared to 45° in [1, 2]).

5. The time period required for the integration of energy quantities to compute one efficiency value has been decreased from 15 minutes to either 5 minutes or one time constant, whichever is larger.

6. In computing efficiency, the gross frontal area of the collector is used instead of aperture area.

7. The efficiency curve is drawn by plotting efficiency versus the difference between inlet fluid temperature and ambient temperature divided by the incident solar radiation. (Average fluid temperature is used in the NBS procedures [1, 2].) Inlet fluid temperature was chosen to be used in the plot primarily because the characteristics of the collector required for the system design procedures as reported in references 9 and 10 can be determined directly from the curve.

The major new features of Standard 93-77 compared to the NBS procedures [1, 2] are:

1. The collector is required to undergo a preconditioning test prior to the start of the thermal tests. The collector must be exposed for three cumulative days with no fluid passing through it and with the mean incident solar radiation measured in the plane of the collector exceeding 17,000 $kJ/(m^2 \cdot day)$.

2. Prior to conducting the efficiency tests, a time constant test is done.

3. After completing the efficiency tests, a series of tests is conducted to determine the collector's incident angle modifier.

4. The entire group of tests may be performed indoors using a solar simulator if desired. The specifications for the simulator are included and follow closely those of references [11-13].

4. Round Robin Program Description

Participants in the program were obtained by soliciting interest with a Sources Sought Announcement in the May 15, 1975 Commerce Business Daily and by individual letters to organizations known to be interested in solar collector testing. The program was designed to provide experimental data from various climatic regions and test facilities on two flat-plate liquid-heating collectors with different heat transfer and optical properties. Final selection of the organizations was made on the basis of test facility experience, climatic and geographic regions, cost to modify facility and labor to conduct the test, and willingness to conduct the test in accordance with the NBS proposed procedure. A total of 21 organizations, including three Government laboratories, as listed in Appendix A, participated in testing each collector. The distribution of participants with respect to geographical and climatic regions is shown in Figure 5.

Because of the large interest in the program, the relatively large number of climatic regions, and the time required to perform the test, it was impractical to send the same two collectors to each participant. Therefore, collectors were selected with sufficiently stable component properties and from manufacturers with established quality assurance methods capable of keeping thermal property variations to a minimum. One collector of each type was shipped to each participant for testing.

Collector No. 1 (PPG Industries) consisted of two 3.2 mm-thick tempered glass cover-plates and an aluminum absorber plate with a flat-black coating assembled into a sealed unit. The assembly was attached to a sheetmetal box containing glass-fiber insulation as shown in Figure 6. Measurements made at the manufacturer's plant of the absorber coating thickness on each of the 21 panels indicated variations from the center to the edge of about 0.0076 mm in the range of 0.0127 to 0.0203 mm. The relationships between coating solar absorptance (α_s), normal emittance (ϵ_n) and thickness are shown in Figure 7. Independent measurement of α_s and ϵ_H (hemispherical emittance) using actual coated samples resulted in values of 0.94 and 0.92, respectively.* The solar transmittance of the glass used in the cover-plate assembly was determined to be 0.85 for an air mass 2 spectral distribution (measurements were made on untempered glass). The glass normal emittance was measured to be 0.85. While the collectors were carefully selected at the manufacturer's plant, no other provisions were made to control the reproducibility of the sample of collectors used in the program. Analysis of the known variations in collector properties indicates that the efficiences should be reproducible to within 1 or 2% if measured under identical conditions.

Collector No. 2 consisted of one 3.2 mm-thick tempered glass cover-plate (Chamberlain Manufacturing Company (CMC)) with a seam-welded mild steel absorber coated with a black chrome selective coating. The absorber was mounted on a thermal insulator and backed with glass-fiber insulation. The entire assembly was mounted in a steel frame with a sheetmetal back and aluminum glazing frame as shown in Figure 8. Spectral reflectance measurements made of six 30.48 cm^2 specimens coated at the same time as the absorber panels indicated a solar absorptance of the black chrome coating of 0.95. The normal emittance of the coatings was measured to be 0.14.** The coating manufacturer*** also measured the solar absorptance and emittance of each panel using portable optical instrumentation. Those results are included in Table 1.

A list of the pertinent dimensions, optical properties, and materials for each collector is presented in Table 1.

5. Results and Statistical Analysis of Data

The primary result reported by each participant was a plot of collector efficiency, η, versus $\left(\frac{t_{f,e} + t_{f,i}}{2}\right)/I$ along with the testing conditions for each of the data points. A summary of the data is given in Table 2 and Table 3 for collectors No. 1 and No. 2, respectively. The values of $F'(\tau\alpha)_e$ and $F'U_L$ were determined by a first-order least-square-fit to all measured data points. Mean and standard deviation values were calculated for these two parameters for the group, using the following statistical equations:

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* Lockheed Palo Alto Research Laboratory, Palo Alto, California.

** Gier-Dunkle Instrument Co., Emissometer Model DB-100, Santa Monica, California

*** Olympic Plating Company, Canton, Ohio.

$$\text{mean} = \bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad (10)$$

and

$$\text{standard deviation} = S = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n}}{n-1}} \qquad (11)$$

The percent deviation from the mean for each set of data points is also shown in the Tables.

An indication of the spread and distribution of $F'(\tau\alpha)_e$ values for each collector are shown in Figure 9. The greater frequency of values about the mean for collector No. 2 is probably due to the fact that more of the data were taken at smaller incidence angles for this collector than for collector No. 1. An early version of ASHRAE Standard 93-77 was out for public review before most participants started testing collector No. 2. Since it required the incident angle to be less than 30° (compared to 45° in the [1, 2]), many participants were undoubtedly influenced to test closer to solar noon.

The relatively large standard deviation of 7.7% for $F'(\tau\alpha)_e$ for collector No. 1 was not expected. It is felt that one major source of the deviation was the use of a "black-and-white" pyranometer, model 8-48, by eight participants. It has been reported [14] that the calibration factor (determined originally with the instrument in the horizontal position) of a similarly-designed instrument changed from 3 to 8% as the instrument was tilted up from the horizontal to typical angles used for collector testing. The mean value of the $F'(\tau\alpha)_e$ values for those collectors (No. 1) where the "black and white" pyranometer was used is 0.79 compared to a mean value of 0.725 for those collectors where an "all-black" (model PSP) pyranometer was used. By arbitrarily reducing the measured $F'(\tau\alpha)_e$ values in Group 1 by 0.065, a new mean value for $F'(\tau\alpha)_e$ for all 21 participants, of 0.73 would result for collector No. 1. This correction would reduce the standard deviation in $F'(\tau\alpha)_e$ to ± 0.05 or ± 6.8%.

Only five of the participants used the "black-and-white" pyranometer for collector No. 2 and the standard deviation was only ± 0.039 or ± 4.64% about the mean of 0.84. In addition, two participants apparently used the gross area rather than the aperture area to calculate the efficiency, which resulted in a 5% low value of $F'(\tau\alpha)_e$. Correction of these values would reduce the standard deviation to ± 0.03 or ± 3.6%.

A similar plot of the distribution of reported values for $F'U_L$ for both collectors is shown in Figure 10. As can be seen, the variation in reported results is large. The standard deviation about the mean of 6.43 $W/(m^2 \cdot °C)$ for the collector No. 1 is ± 1.01 $W/(m^2 \cdot °C)$ or ± 15.7%. For collector No. 2, the mean is 4.37 $W/(m^2 \cdot °C)$ with a standard deviation of ± 1.20 $W/(m^2 \cdot °C)$ or ± 27.7%. In order to explain the variation, a close examination was made of the reported data.

As shown in Figure 6 for collector No. 1, the absorber plate is in thermal contact with the outside mounting and cover-plate frame. Therefore, the edge losses are dependent upon the collector array mounting configuration and can be particularly significant when an individual panel is exposed. The influence of edge losses in $F'U_L$ is shown in Figure 11. The variation, from no edge loss to an edge loss of about 3 times the value of 0.5 $W/(m^2 \cdot °C)$ for a typically insulated edge, results in a percentage difference of + 7% to -26% from the mean value of $F'U_L$ reported for the collector.

Each participant was requested to enclose the No. 1 collector in a 5 cm x 10 cm frame with a plywood backing to provide a more uniform test situation for this collector. A review of the collector mounting procedures plus the description of the actual tests indicated that some unusual conditions did exist. For example, extra insulation was used around the back and edges of some of the collectors, mass flow rates different from the prescribed 0.02 $kg/(s \cdot m^2)$ were used, and incidence angles exceeded 45 degrees in some cases. By omitting these data from the analysis, a new mean value of $F'U_L$ of 6.56 $W/(m^2 \cdot °C)$ would result with a standard deviation of ± 0.75 $W/(m^2 \cdot °C)$ or ± 11.4%.

The influence of one extreme value for $F'U_L$ for collector No. 2 had a large effect on the statistical analysis. By considering the value of 1.6 $W/(m^2 \cdot °C)$ to be an outlyer [15] and therefore omitted, the mean value of $F'U_L$ would become 4.58 $W/(m^2 \cdot °C)$ and the standard deviation ± 0.775 $W/(m^2 \cdot °C)$ or ± 16.8%.

The significantly lower overall loss coefficient for collector No. 2 is due in part to better thermal insulation of the absorber plate from the exterior environment and the use of a selective coating. However, the single glazing makes the collector heat loss more susceptible to wind and ambient temperature. The range in measured values of overall loss coefficient for the five collectors that exhibited $F'(\tau\alpha)_e$ values of 0.85 (very close to the corrected mean of 0.844) are + 20% and - 17% from the mean as illustrated in Figure 12.

6. Analysis of the Effect of Environmental Conditions

It was felt that the range of environmental conditions existing during the tests at the various facilities across the country undoubtedly caused a portion of the data scatter. In order to determine the amount, one of the round robin participants, W.C. Thomas and his graduate student A.G. Dawson, III of Virginia Polytechnic Institute and State University undertook a detailed analysis of the data. The results of that study are reported in this Section [16]. The general approach used was to reference all measured thermal efficiencies to a common set of environmental conditions by using analytical models for the two flat-plate collectors tested.

Screening and Selection of Data

The data were examined for complete documentation and consistency with respect to test conditions. The objective was to assemble at least ten complete sets of data. It should be noted that regional location, altitude, and climatic conditions at the testing laboratories were not criteria for screening the data. After the screening process, 12 sets were selected for collector No. 1 (PPG) and 10 sets were selected for collector No. 2 (CMC). Typically, test results were not included in the analysis because diffuse fractions, wind speed, ambient temperature, incident angles, or type of test fluid were not available. In some cases, the calculated results required by [1, 2] were incomplete. Where possible, these were completed and the results used. For example, incident angles were calculated provided the times of testing and collector orientation were reported. Results for more than the required 16 data points were given by some participants. For these cases, the 16 points nearest solar noon were selected. The additional points were not included to avoid weighting the particular facility more heavily than the others.

The data corresponding to the figures to be shown in this Section are tabulated in Appendix B. Testing organizations are identified by the letter designation of Tables 2 and 3. The solid curves shown are least-squares second-order polynomials unless noted otherwise. Following reference [17], the mean value of the square of the distance from the points to the curve ("mean square") is used to compare the closeness of correlations.

Figure 13 shows the efficiencies as reported by the 12 selected organizations for collector No. 1. The abscissa values were recalculated from the data so that the efficiency curve could be drawn using inlet fluid temperature instead of average fluid temperature. This abscissa selection makes the plot consistent with [4]. The points shown to the left of the ordinate axis are for tests where the inlet temperature was less than the ambient temperature. Participant K reported two measurements where the abscissa was outside the range shown. While the results were included in the statistical analysis, the points are not shown in the graphs. The second-order curve shows an increasing slope as $\frac{t_{f,i} - t_a}{I}$ increases contrary to what would be expected if all data were taken at one laboratory.

Identification of the data points in Figure 13 with each participant showed, generally, a small amount of scatter for individual organizations. The spread, consequently, results from the differences in efficiency values, at the same conditions, by the various organizations. The ordinate intercept for the second-order curve shown is 0.731.

Figure 14 shows the results reported for collector No. 2 as reported by the 10 selected participants. Generally, the efficiencies reported by the different laboratories agree more closely than do those in Figure 13. Since this was the second collector tested and since the collector was less sensitive to the method of mounting on the test frame, the trend is as expected. The second-order curve has a continuously decreasing slope with an ordinate intercept of 0.80.

Figures 15 and 16 show a subset of the above-selected test results where each facility shown reportedly adhered to the more stringent requirements of ASHRAE Standard 93-77 [4]. There were five organizations (A, G, H, J, N) testing the collector No. 1 and seven organizations (G, H, J, N, O, R, U) testing collector No. 2 that reportedly met these requirements. Figures 15 and 16 show clearly that the differences are much more pronounced from test facility to test facility compared to the scatter reported by a given facility. There is much less scatter associated with test results shown in Figure 15 and 16 than in Figures 13 and 14, respectively.

Analysis Approach

The principal task was to determine how much of the scatter about the curves, as shown in Figures 13 through 16, could be attributed to the differences in environmental conditions under which the tests were conducted. The analysis approach involved adjusting each of the efficiency values or data points up or down depending on whether the combined effect of the actual test environment would theoretically result in a higher or lower efficiency if the same test were conducted at a "reference" set of conditions. The criterion for evaluating the effect of the data adjustment was to compare the before and after values of the mean square of the regression analysis.

Measured efficiencies as reported were adjusted to a common set of conditions by subtracting the theoretically-determined efficiency at actual (experimental) conditions from the theoretical efficiency at the common ("reference") condition and adding the result algebraically to the experimentally-determined efficiency. The expression for the corrected efficiency is

$$\eta\ (\text{std. conditions, corrected}) = \eta\ (\text{actual conditions, measured}) + [\eta\ (\text{std. conditions, theoretical}) - \eta\ (\text{actual conditions, theoretical})] \quad (12)$$

Applying the correction required a theoretical thermal performance analytical model and the configuration, dimensions, and heat transfer properties for each collector. It should be noted, however, that the theory was used only to determine an efficiency difference. Therefore small uncertainties in collector properties and the analytical model would have had an even smaller effect on the corrected efficiency values.

"Reference" conditions selected were generally the mean values of the reported test conditions reported with round-off to convenient values. This criterion for a set of "reference" conditions resulted in the minimum overall adjustment of data. The "reference" environmental conditions selected are shown in Table C1 of Appendix C.

Description of Analytical Model

The collector model used was based on state-of-the-art collector theory as summarized in reference [6]. Extensions have been made to account for the effects of the scattered component of solar radiation and temperature and composition of the heat transfer fluid. The presence of scattered radiation effectively changes the transmittance of the cover-plate assembly. Scattered radiation is accounted for by considering two limiting cases. The scattered radiation is assumed to be either completely diffuse or from an apparent origin near the sun.

All the test facilities which furnished the results under consideration used either water or ethylene glycol-water mixtures as the transfer fluid. The properties of glycol mixtures, as functions of temperature and concentration, were taken from reference [18] and programmed as an interpolation table.

The complete details of the model and equations and how they were solved are given in Appendix C.

Use of the Analytical Model

After the data were compiled, a set of cards was prepared for each test facility with operating conditions, environmental conditions, and measured efficiencies encoded. The collector design parameters and "reference" conditions were, of course, the same for all test facilities. Corrections to the measured efficiencies were then made progressively by accounting for one operating environmental variable at a time. Using the inlet fluid temperature in the abscissa rather than the mean fluid temperature resulted in a considerable simplification. Had the mean fluid temperature been used, it would have been necessary to carry out a separate calculation to correct the mean fluid temperature to "reference" conditions. As the corrections to "reference" conditions were applied progressively, the mean squares were used to evaluate the effectiveness of that particular correction. In addition, the graphs were studied visually by superimposing them on previous graphs to observe trends.

A separate statistical analysis plot routine and package were used to prepare the graphs. The graphs were drawn by a Calcomp plotter in conjunction with Virginia Polytechnic Institute and State University's IBM 370/158 digital computer. Second-order polynomial representations of collector efficiency were used since the representation essentially duplicated the results of the analytical model at "reference" conditions. (The mean squares of the fits to the standard theoretical curves were less than 0.02). Other considerations that were taken into account in the decision to use the second-order equation include the requirements of ASHRAE 93-77 [4] and the observation that a linear fit gives somewhat higher than expected values of the ordinate intercept $F_R(\tau\alpha)_e$.

Results

The results with all the environmental and operating conditions considered are shown graphically in this section and in tabular form in Appendix B.

In all the graphs that show discrete efficiency points, the solid lines are least-squares curves rather than a comparison per se with the theoretical model.

Figures 17 through 20 show the theoretical effect on efficiency of environmental conditions. The abscissas correspond approximately to the ranges reported in the round robin program. The curves show the effect of a single parameter with the others constant at "reference" values. Note that $(t_{f,i} - t_a)/I$ is held constant for each plot. The effects of parameters depend strongly on the inlet temperature. The two inlet temperatures selected to depict the results are 10°C and 70°C above ambient which brackets the recommended test range [1, 2, 4]. In view of Figures 17 through 20, the expected efficiency changes resulting from correcting to "reference" conditions are generally not large, as will be shown below, compared to the more extreme differences noted in Figures 13 through 16.

Figure 21 shows the theoretical efficiency values calculated for collector No. 1 for the actual conditions reported by the 12 selected participants. The curve has a slightly increasing slope. The shape indicates that this combination of environmental conditions overshadows the increase of U_L with temperature. The scatter about the curve is, of course, justified in the absence of any experimental error. The efficiency spread at the abscissa value of 0.07 $(°C \cdot m^2)/W$ is pronounced but does not completely account for the spread at the corresponding value in Figures 13 and 15. Figure 22 shows the calculated efficiency for collector No. 1 at "reference" conditions. Figure 23 shows efficiencies corrected for all environmental and operating conditions. The mean squares are reduced from 27.9 in Figure 13 to 20.6 (percentage points-squared) in Figure 23. It is significant to note that the increasing slope is essentially removed in Figure 23 as a result of the correction.

Figure 24 shows the theoretical efficiencies calculated for the collector No. 1 tests that reportedly met ASHRAE 93-77 requirements. The slightly increasing slope observed in Figure 15 is suppressed and the scatter is not as large. Figure 25 shows the corrected efficiencies. The mean square is reduced from 23.2 in Figure 15 to 17.1 in Figure 25 as a result of accounting for the differences in test conditions. The mean square of 17.1 in Figure 25 is less than the value of 20.6 in Figure 23.

The theoretical efficiency values for the actual test conditions are shown for collector No. 2 in Figure 26. Here, as for all the collector No. 2 curves, the combination of test conditions and collector performance characteristics result in a second-order curve with a slightly decreasing slope. The scatter resulting from different test environments is again substantial but does not fully account for the scatter observed in Figure 14. The theoretical efficiency curve at "reference" conditions is shown in Figure 27.

Applying the corrections to the efficiencies shown in Figure 14, the result for collector No. 2 is shown in Figure 28. The mean square is reduced from 17.5 to 13.5 in accounting for different environmental and test conditions. Many of the points that are farther away from the best-fit curve still appear in Figure 28. Restricting the results to those tests which reportedly met ASHRAE 93-77 conditions, Figure 29 shows the theoretically justifiable scatter. Figure 30 shows the corresponding corrected results from the seven organizations. Comparing Figure 28 with Figure 30, many, but not all, of the larger differences are eliminated. The mean square is reduced from 8.5 in Figure 16, to 7.2 in Figure 30. A large reduction in scatter is observed in simply going from Figure 14, with a mean square of 17.5, to Figure 16 with 8.5. On the other hand, the mean square for the corrected results in Figure 28 is only about 23 percent lower than for Figure 14.

Figures 16 and 30 show that the efficiencies reported by participant 0 are significantly lower than those reported by the other six participants. Figures 31 through 33 show the consensus of the results from the other six organizations. The mean square is substantially reduced. The correction process reduces the mean square from 4.6 in Figure 31 to 4.0 in Figure 33. The best correlation obtained in the study, without arbitrarily omitting results, is that shown in Figure 33.

Linear best-fit curves, corresponding to the four principal figures, are shown in Figure 34-37. These curves are included so that the intercepts and slopes can be compared with the results obtained from all 21 organizations.

Table 4 is a summary of the pertinent statistical information for linear and second-order least-squares fits to the various sets of efficiencies.

In conducting this analysis, it could not be concluded which of the two limiting cases that were considered best accounts for the effects of scattered radiation. Assuming scattered radiation originates from a direction near the sun, the cover transmittance is the same for beam and scattered radiation. In the other limiting case, scattered radiation was considered completely diffuse and a correction was applied. However, the overall effects on efficiencies resulting from these corrections were considerably less than the experimental uncertainties.

Attempts to investigate the sensitivity of the correlations to sky temperatures were also inconclusive. Sky temperatures of ambient minus 6°C for summer and ambient minus 20°C for winter [6] were used in place of equation (6) of Appendix C. The mean squares changed by less than 1.0 when compared to the corresponding plots using equation (6). Although sky temperatures may have a significant effect on measured efficiency, the effect could not be identified from the information available.

An attempt was made to test the adequacy of the correlations for wind, percent scattered, etc. It was not possible to evaluate the individual correlations because of the relatively large amount of scatter in the results after all other corrections had been made.

The effect of different techniques for mounting collectors on test frames, which would change the back and side insulation, was considered. Again, no general trends could be associated with the mounting technique.

In general, the results from the collector No. 1 tests show more scatter than the results from the later collector No. 2 tests. The correction procedure, however, reduced the amount of scatter more for the former test results. Applying corrections progressively, each effect considered either reduced the mean square or resulted in a change too small to determine a definite trend. Individual large deviations from the best-fit curve were reduced significantly. The many points clustered closer, however, were changed with less consistent trends. The combined effect resulted in changes of the mean square which were small. The scatter remaining after the corrections were applied is attributed primarily to experimental and data reduction errors and will be addressed in Section 7. However, the limitation of the correction theory and the possibility of differences between the 12 collectors must be considered. It is also recognized that normal outdoor weather can have an adverse effect on measuring and recording apparatuses.

Figures 38 and 39 show, for the two collectors used in the round robin program, theoretical curves for more favorable and less favorable combinations of environmental conditions. These hypothetical limiting-case combinations are based on conditions and ranges allowed by ASHRAE 93-77. The graphs are included to show the importance of referencing efficiencies to a common environment. The approach developed herein could be extended and verified to apply more generally to flat-plate collectors.

7. Analysis of The Effect of Random and Systematic Errors

As shown in Section 6 of this report, there was considerable scatter in the data when considered as a combined group (i.e., Figures 13 and 14); however, the data for an individual facility were generally consistent and showed very little scatter. In addition, correcting the data for the different environmental conditions that existed from facility to facility was shown to reduce the scatter between facilities by less than 30%. Therefore, one concludes that either the requirements of the test are not restrictive enough or that there were systematic errors which were not accounted for by the various participants. In order to examine those possibilities, another round robin participant, B.D. Wood of Arizona State University, conducted the analysis reported in this Section.

The data taken during a given test are recorded and reduced to a plot of thermal efficiency, η, versus the parameter $(t_{f,i} - t_a)/I$, here called X. Each measurement has associated with it a random or uncertainty error and a systematic error such that (the specific heat is assumed to be known exactly):

$$\eta \pm w_\eta \pm \Delta\eta = \frac{(\dot{m} \pm w_{\dot{m}} \pm \Delta\dot{m})\, c_p[(\Delta t_f \pm w_{\Delta t_f} \pm \Delta(\Delta t_f)]}{(I \pm w_I \pm \Delta I)\,(A \pm w_A \pm \Delta A)} \qquad (13)$$

$$X \pm w_X \pm \Delta X = \frac{[(t_{f,i} \pm w_{t_{f,i}} \pm \Delta t_{f,i}) - (t_a \pm w_{t_a} \pm \Delta t_a)]}{(I \pm w_I \pm \Delta I)} \tag{14}$$

where $\Delta t_f = t_{f,e} - t_{f,i}$

w = random or uncertainty error which could be either positive or negative with the same probability. The sign of w is indeterminant.

Δ = systematic error. The sign could be either positive or negative and will remain fixed for a given test apparatus (e.g., conduction errors for thermocouple measurement, calibration error for pyranometer, or radiation error for ambient air temperature measurement).

Random errors cause data scatter for a particular test facility. Systematic errors cause a disagreement between test facilities. Since there is relatively small scatter (less than 4%) for a given test facility, it is reasonable to assume that the discrepancies among the combined data are due primarily to systematic errors at the facilities. However, if the test specifications were not tight enough, similar discrepancies could occur.

First consider the scatter that could be attributed to the experimental uncertainty in the specifications of the test in [1, 2] and [4]. The maximum uncertainty or error allowable is:

$$w_\eta = \pm \quad \frac{\partial \eta}{\partial \dot{m}} w_{\dot{m}} + \frac{\partial \eta}{\partial \Delta t_f} w_{\Delta t_f} + \frac{\partial \eta}{\partial I} w_I + \frac{\partial \eta}{\partial A} w_A \tag{15}$$

or,

$$\frac{w_\eta}{\eta} = \pm \quad \frac{w_{\dot{m}}}{\dot{m}} + \frac{w_{\Delta t_f}}{\Delta t_f} + \frac{w_I}{I} + \frac{w_A}{A} \tag{16}$$

Similarly,

$$\frac{w_X}{X} = \pm \quad \frac{w_{t_{f,i}} + w_{t_a}}{(t_{f,i} - t_a)} + \frac{w_I}{I} \tag{17}$$

The allowable uncertainty or inaccuracy in the measurements as specified in or estimated from [1, 2] and [4] are such that:

$$\frac{w_{\dot{m}}}{\dot{m}} = \pm\, 0.01$$

$$w_{\Delta t_f} = \pm\, 0.1°C$$

$$\frac{w_I}{I} = \pm\, (0.03 + \frac{0.1}{I})$$

$$\frac{w_A}{A} = \pm\, 0.01$$

$$w_{t_{f,i}} = \pm\, 0.5°C$$

$$w_{t_a} = \pm\, 0.5°C$$

Therefore

$$\frac{w_\eta}{\eta} = \pm\, (0.05 + \frac{0.1}{\Delta t_f} + \frac{0.1}{I})$$

$$\frac{w_X}{X} = \pm\, (0.03 + \frac{1.0}{t_{f,i}-t_a} + \frac{0.1}{I}) \tag{19}$$

From [1,2] and [4], $I \geq 630\ W/m^2$, therefore equations (18) and (19) become:

$$\frac{w_\eta}{\eta} \leq \pm\, (0.0502 + \frac{0.1}{\Delta t_f})$$

$$\frac{w_X}{X} \leq \pm\, (0.0302 + \frac{1.0}{t_{f,i}-t_a}) \tag{21}$$

Considering collector No. 2, the following typical test values are taken from Tables 1 and C1:

$A = 1.79\ m^2$

$\dot{m} = 0.0358\ kg/s$

$c_p = 4187\ J/(kg \cdot °C)$

$I \geq 630\ W/m^2$

$t_a = 20°C$

Then, and noting that Δt_f can be calculated by:

$$\Delta t_f = \frac{\eta\ I\ A}{\dot{m}\ c_p} \tag{22}$$

$$\Delta t_f \geq 7.523\eta \tag{23}$$

$$t_{f,i} \geq 20 + 630X \tag{24}$$

and

$$\frac{w_\eta}{\eta} \leq \pm \left(0.0502 + \frac{0.10}{7.523\eta}\right)$$

$$\frac{w_X}{X} \leq \pm \left(0.0302 + \frac{1.0}{630X}\right) \tag{26}$$

Equations (25) and (26) can be used to define the "maximum error" band for the test data for collector No. 2. For example, the data in Figure 37 can be correlated by:

$$\eta = 0.814 - 4.98X \tag{27}$$

Then for each value of X and corresponding η, the maximum error band allowable from references [1, 2] and [4] can be calculated as follows:

X	0.01	0.05	0.10
η	0.764	0.565	0.316
$\frac{w_\eta}{\eta}$	± 0.068	± 0.074	± 0.092
w_η	$\pm$ 0.052	$\pm$ 0.042	$\pm$ 0.029
$\frac{w_X}{X}$	± 0.189	0.062	0.046
w_X	$\pm$ 0.0019	$\pm$ 0.0031	$\pm$ 0.0046

Figure 40 is a replot of Figure 36 where all the uncorrected data for collector No. 2 for the 10 selected participants is shown along with the maximum error band defined above. Figure 41 is a similar plot but for only those participants which reported adhering strictly to the requirements of ASHRAE Standard 93-77. Figures 42 and 43 are corresponding plots after the data have been corrected to "reference" conditions.

Since the data of Figures 41 and 43 all lie within the this error band, one might conclude that the scatter was due entirely to allowable uncertainty as specified in references [1, 2] and [4] and no systematic error existed at the facilities shown in Figures 41 and 43. It can more logically be assumed that the data scatter among the various test facilities taken as a group would most probably follow some sort of randomness and be considerably less than the maximum allowable error band. Therefore, a second analysis was done.

A numerical experiment was conducted to determine the "anticipated" data scatter from 10 hypothetical test facilities, each claiming compliance with ASHRAE 93-77. Table 5 is a matrix of possible errors associated with each measurand. The probability of each error is the same (this is conservative compared to a normal probability distribution about the mean). A UNIVAC library program was used to generate a random number between 0 and 1.0. This number with a corresponding error selected from Table 5 for each measurand at the ten hypothetical facilities was then used to select the appropriate error. Hence, 60 random numbers between 0 and 1.0 were required to generate Table 6, which is a tabulation of errors assigned with each measurement at each of the 10 hypothetical test facilities. The collector computer model described in Appendix C was used to obtain an efficiency curve for collector No. 2. This curve was then used to calculate the temperature rise across the collector for a given collector inlet temperature at the following conditions:

$$I = 1000 \text{ W/m}^2 \text{ or } 630 \text{ W/m}^2$$

$$A = 1.79 \text{ m}^2$$

$$\dot{m} = 0.0358 \text{ kg/s}$$

$$t_a = 20°\text{C}$$

$$t_{f,i} = 20, 30, 40, 50, \ldots °\text{C}$$

Then in order to calculate the supposedly measured efficiencies for each collector at the 10 test facilities, the following relationships were used:

$$I_j = 1000 + \Delta I_j \text{ or } 630 + \Delta I_j \tag{28}$$

$$A_j = 1.79 + \Delta A_j \tag{29}$$

$$\dot{m}_j = 0.0358 + \Delta \dot{m}_j \tag{30}$$

$$t_{a_j} = 20 + \Delta t_{a_j} \tag{31}$$

$$t_{f,i_{j,k}} = t_{f,i_k} + \Delta t_{f,i_j} \tag{32}$$

$$\Delta t_{j,k} = \Delta t_k + \Delta\Delta t_j \tag{33}$$

These supposedly measured efficiencies are shown in Figures 44 and 45 for an insolation of 630 W/m^2 and 1000 W/m^2, respectively. As expected, the scatter is considerably less than the "maximum" error band also shown in the Figures. By comparing Figures 43 and 45, one concludes that the data scatter that actually occurred (after the data were corrected for differences in operating and environmental conditions) among those facilities that reportedly adhered to ASHRAE Standard 93-77 was much larger than should be expected. Also notice that the combined errors in the numerical experiment only shifted the curve up or down without changing the slope. Therefore, systematic facility errors undoubtedly existed. Unfortunately, an evaluation of the experimental apparatuses and various experimental techniques of the various participants was not performed.

Each participant was provided with a copy of the test procedure which describes the accuracy, precision and calibration requirements for each measurement. However, meeting these requirements does not preclude the possibility of uncertainties arising from sensor installation, data acquisition, or data reduction.

Based on the data available, it is only possible to hypothesize that some combination of the following systematic errors caused a portion of the data scatter:

Systematic Facility Errors:

- heat transfer between the test apparatus and the collector (proximity of heat sources to the collector)
- reduced heat losses to ambient due to shielding of collector support stand
- test apparatus not at steady state or "quasi-steady-state" conditions during tests
- change in specific heat of the transfer fluid
- inexperienced technicians conducting the tests.

Systematic Instrumentation Errors:

- conduction errors in thermocouple installations
- pyranometer calibration error
- flow meter calibration error

8. Implication of Collector Performance Uncertainty on System Performance

The significance of the variation in the reported performance for a particular collector can be illustrated by calculating the expected system performance for two sample solar systems.

For the first example, the performance was calculated for a typical combined solar domestic hot water and space heating system. A residence located in Madison, Wisconsin with a design heat loss of 21 kW was selected. A hot water demand of 0.32 m^3 per day combined with the space heating load resulted in an average monthly energy requirement for the year of about 1.7×10^9J. The solar energy system assumed consisted of 80 m^2 of collector No. 1. Other system features included a heat exchanger between the collector and storage, an insulated 3.8 m^3 liquid storage tank, a domestic hot water heat exchanger and preheat storage tank with suitable pumps and controls. Auxiliary energy was supplied when sufficient energy was not available from thermal storage.

The calculation of the fraction of the load supplied by solar energy was performed using the f-chart method [9]. The collector thermal performance factors used for $F'(\tau\alpha)_e$ and $F'U_L$ are listed in Table 4 for the mean, "best" and "worst" values as reported in Section 5 of this report. The results show a deviation of + 10.3 and - 11.8 percentage points in yearly solar fraction from the mean value or a total spread of 22.1 percentage points.

A second sample problem was completed again using the f-chart technique. A solar domestic hot water system was simulated in five different cities across the country. For this calculation, it was assumed that 5.37 m^2 of collector No. 2 without a heat exchanger were used. The relationship between F' and F_R was taken from reference [6]. The collector was assumed tilted at an angle equal to the latitude and the system used a 0.45 m^3 storage tank. The system supplied hot water at a constant temperature of 60°C with a constant inlet temperature which varied from city to city as shown in Table 8 and 9. The system was simulated using the collector performance factors from all 10 test facilities identified in Section 6 of this report. Table 8 shows the calculated yearly fraction of the hot water load supplied by solar energy using data from the six facilities adhering to the requirements of ASHRAE Standard 93-77. The maximum spread is 6.5 percentage points for Washington, D.C. Table 9 shows the results using data from test facilities reporting the five highest and the five lowest performance. Again the maximum spread occurs in Washington, D.C., 17.8 percentage points.

9. Conclusions

The results of the analysis indicate that the majority of the reported differences in measured collector efficiency in the round robin testing program resulted from experimental error or systematic differences from facility to facility rather than from differences in the outdoor test environments.

The preparation and mounting of the collector for test appeared to cause a large uncertainty in test results for collector No. 1.

The use of a pyranometer meeting the World Meteorological Organization Class I requirements and a pyranometer calibrated for use at test tilt angles was found to be of major importance.

The environment can have a significant effect on the measured collector efficiency even when conditions prescribed by current standards are met. Within the limitation of the accuracy of flat-plate collector performance theory, it was found that test results could be referenced to a common environment using a straightforward analytical procedure. The procedure significantly reduced the differences in measured efficiencies reported by the various participants.

Efficiency correlations from individual participants generally showed small scatter. Larger differences were observed, however, between efficiencies measured by various participants at approximately the same conditions. The second series of tests (on collector No. 2) gave more consistent results than the first.

Tests that reportedly met the more restrictive ASHRAE 93-77 requirements showed much more consistency among participants. It was not apparent, however, whether the improvement resulted from the additional restrictions or better experimental procedures by those participants. By restricting efficiency measurements for collector No. 2 to 6 of the 7 participants reportedly meeting ASHRAE 93-77 requirements, highly consistent results were observed.

It is felt that outdoor solar collector testing will continue to be performed at an ever increasing rate. The technique of correcting test results to "reference" conditions is a potentially useful aid for the solar collector industry. The technique should be validated and then packaged into a useful tool that could easily be utilized within the industry. In addition, procedures need to be adopted to ensure facility-to-facility agreement. Continuing experiments would be desirable where two or three "independent" facilities would conduct a series of tests and insure intercomparability. The facilities would be picked so that extremes in environmental conditions could be studied. The tests might include:

- interchanging collectors

- determining the effect of environmental conditions on data scatter and reproducibility (wind, sky temperatures, insolation level, percent diffuse, ambient temperature)

- intercomparison of pyranometers

- determining the spectral distribution of the radiation for the three locations

- determining when steady conditions occur for thermal testing.

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Table 1. Pertinent Collector Characteristics
(from the manufacturer's literature)

Characteristics	Collector No. 1	Collector No. 2
Manufacturer	PPG Industries	Chamberlain Mfg. Co.
Gross dimensions (m)	1.93 x 0.86	2.14 x 0.92
Gross area (m^2)	1.74	1.96
Effective aperture area (m^2)	1.60	1.79
Weight per gross area (kg/m^2)	31.8	37.0
Volumetric capacity per gross area (m^3/m^2)	0.72×10^{-3}	Unknown
Pressure drop across collector (Pa) (at operating mass flow rate)	0.83	1.6
Cover plate assembly		
Number of glass plates	2	1
Material	Herculite glass	Fourco-Cleartemp
Dimensions (m)	1.90 x 0.84	2.08 x 0.86
Solar transmittance (single glass)	0.85	0.90
Hemispherical emittance	0.84	0.88
Coefficient of expansion (mm/mm/°C)	Unknown	2.78×10^{-6}
Specific heat J/(kg·°C)	857.7	Unknown
Absorber Plate		
Material	Aluminum	Mild steel
Dimensions	1.90 x 0.84	2.09 x 0.86
Flow configuration	13 parallel pass	19 parallel pass
Coating	Durachron 600 L/G flat black	Black chrome
Solar absorptance	0.94	0.94
Hemispherical emittance	0.92	0.12
Air space(s)		
Between covers (mm)	9.53	---
Between cover and absorber (mm)	12.7	19.0
Insulation		
Material	Glass-fiber	Glass-fiber
Density (kg/m^3)	48.1	~80
Thickness (mm)	76.2	76.2
Thermal conductivity (W/m·°K)	0.035	Unknown

Table 2. Summary of the Thermal Performance Data for Collector No. 1

Source Identification	$F'(\tau\alpha)_e$	$F'(\tau\alpha)_e$ Deviation %	Incidence Angle degreea	Tilt Angle degrees	$F'U_L$ $W/(m^2 \cdot {}^\circ C)$	$F'U_L$ Deviation %	Percent Diffuse %	Wind Speed m/sec	Pyranometer Model	Fluid Flow Rate $Kg/(s \cdot m^2)$
A	0.81	+ 7.7	?	45	6.92	+ 7.6	8 to 15	8.5 to 10.2 1.8 to 4.5	PSP	0.025
B	0.79	+ 5.0	16 to 44	47	4.48	-30.3	?	0	8-48	0.028
C*	0.70	- 6.9	0 to 30	30	5.47	-14.9	?	1.3 to 2.7	Model 2	0.195
D	0.83	+10.4	11 to 26	45	7.58	+17.9	?	1.3 to 2.7	8-48	?
E	0.73	- 2.9	19 to 23	45	7.29	+13.4	14 to 40	3.1 to 5.4	8-48	0.012
F	0.78	+ 3.7	?	30	6.07	- 5.6	10 to 19	0.5 to 3.6	663 (M-G)	0.022
G	0.73	- 2.9	± 1	14 to 38	7.35	+14.3	9 to 11	0.0 to .08	PSP	0.017
H	0.68	- 9.6	>5	31	5.79	-10.0	15 to 32	0.9 to 5.4	PSP	0.016
I	0.83	+10.4	0 to 5	45	5.20	-19.1	7 to 10	0.0 to 1.6	SR-75	0.035
J	0.79	+ 5.0	2 to 12	20 to 25	6.71	+ 4.4	10 to 18	0.9 to 2.7	Model 2	0.019
K	0.87	+15.6	13 to 39	48	6.27	- 2.5	15 to 20	2.2 to 4.5	8-48	0.017
L	0.72	- 4.6	25 to 28	45	7.12	+10.7	17 to 27	2.2 to 4.9	8-48	0.019
M	0.75	-	15 to 23	40	5.53	-14.0	12 to 22	0.1 to 0.5	8-48	?
N	0.75	-	7 to 18	25	7.70	+19.8	10 to 30	0.6 to 3.0	PSP	0.017
O	0.67	-10.9	40 to 55	60	8.50	+32.2	10 to 23	1.8 to 3.6	PSP	0.020
P	0.71	- 5.6	30 to 60	42	5.74	-10.7	11 to 34	$\geq$ 0.8	PSP	?
Q	0.79	+ 5.0	10 to 48	25 to 35	7.15	+11.2	12 to 20	1.2 to 4.6	8-48	0.020
R	0.79	+ 5.0	~ 0	17 to 25	5.76	-11.8	~12	2.0 to 4.0	8-48	0.020
S	0.67	-10.9	~ 0	5 to 10	7.17	+11.5	?	2.2 to 4.5	180° pyro	0.004 to 0.015
T	0.67	-10.9	2 to 18	24 to 55	5.67	-11.8	9 to 20	2.0 to 5.0	PSP	0.032
U	0.74	- 1.6	2 to 25	32	5.56	-13.5	9 to 12	0.2 to 8.0	PSP	0.070
Mean	0.75				6.43					
Standard Deviation	$\pm$0.586				$\pm$1.01					
% Deviation	$\pm$7.7%				$\pm$15.8%					

* measured using a calorimetric method

? data not available

– not applicable

Table 3. Summary of the Thermal Performance Data for Collector No. 2

Source Identification	$F'(\tau\alpha)_e$	$F'(\tau\alpha)_e$ Deviation %	Incidence Angle degrees	Tilt Angle degrees	$F'U_L$ $W/(m^2 \cdot {}^\circ C)$	$F'U_L$ Deviation %	Percent Diffuse %	Wind Speed m/sec	Pyranometer Model	Fluid Flow Rate $kg/(s \cdot m^2)$
A	0.86	+ 2.4	<30	45	5.32	+19.6	10 to 17	0.2 to 10.4	PSP	0.018
B	0.80	- 4.8	<30	47	3.05	-31.5	?	0 to 1.0	8-48	0.02
C*	0.76	- 9.5	0 to 30	40	4.57	+ 2.7	?	1.3 to 2.6	Model 2	0.05
D	0.85	+ 1.2	1 to 10	?	3.90	-12.4	?	0.1	PSP	0.025
E	0.80	- 4.8	3 to 16	?	4.10	- 7.9	11 to 17	0.7 to 4.5	8-48	0.008
F	Not reported									
G	0.87	+ 3.6	0	26-51	5.51	+23.8	11 to 16	1.0 to 5.0	PSP	0.02
H	0.85	+ 1.2	?	40	5.18	+16.4	10 to 16	1.3 to 4.5	Model 2	0.02
I	0.89	+ 6.0	0 to 1	26-50	3.02	-32.1	4 to 10	0.3 to 1.4	SR-75	0.02
J	0.83	- 1.2	1.5 to 13	37-48	4.50	+ 1.1	5 to 22	0.5 to 2.7	PSP	0.020
K	0.83	- 1.2	0	45	5.22	+17.2	?	0 to 10.0	SR-75	0.026
L	0.88	+ 4.8	6 to 9.6	45	3.77	-15.3	14 to 22	0 to 2.2	8-48	0.020
M	0.85	+ 1.1	2 to 41	35	6.26	+40.6	17 to 30	0.1 to 0.5	8-48	0.032
N	0.86	+ 3.6	3.3 to 8	60	5.01	+12.6	3 to 13	0.6 to 5.0	PSP	0.035
O	0.82	- 2.3	5 to 14	59.5	4.90	+10.1	7 to 15	0.9 to 5.3	PSP	0.022
P	0.76	- 9.5	7 to 31.5	32.5	1.60	-64.0	?	<1.0	PSP	0.032
Q	0.85	+ 1.2	4 to 26	37	5.50	+23.6	7 to 34	0 to 4.5	8-48	0.020
R	0.83	- 1.2	0 to 5	?	4.39	- 1.3	8 to 19	2.2 to 5.5	PSP	0.035
S	Not reported									
T**	0.72	-14.0	0 to 10	34	-4.11	- 7.6	13 to 23	0 to 3.0	PSP	0.04
U	0.85	+ 1.2	4 to 20	43	4.31	- 2.0	26 to 43	0.3 to 2.6	PSP	0.018
Mean	0.84				4.45					
Standard Deviation	±0.036				±1.11					
% Deviation	+4.64				±24.9					

* measured using a calorimetric method
? data not available
– not applicable
** data received too late to be included in the standard deviation analysis

Table 4. Summary of Ordinate-Intercepts, Slopes, and Mean Squares Values for Efficiency Correlations

Efficiency Set		No. of Values	Linear Curve			Second-Order	
			Intercept	(-)Slope*	Mean Sq.	Intercept	Mean Sq.
No. 1	Uncorrected	192	0.705	5.61	30.5	0.731	27.9
	Corrected	192	0.728	5.98	20.6	0.733	20.6
	Theoretical	192	0.692	5.71	2.46	0.696	2.4
	Uncorrected ASHRAE	80	0.707	6.30	23.2	0.722	23.2
	Corrected ASHRAE	80	0.726	6.51	16.8	0.728	17.0
	Theoretical ASHRAE	80	0.691	5.72	1.5	0.693	1.5
No. 2	Uncorrected	160	0.813	4.82	18.0	0.798	17.5
	Corrected	160	0.816	5.11	13.8	0.806	13.5
	Theoretical	160	0.814	4.98	4.0	0.802	3.7
	Uncorrected ASHRAE	112	0.820	4.77	8.8	0.807	8.5
	Corrected ASHRAE	112	0.824	5.08	7.5	0.811	7.1
	Theoretical ASHRAE	112	0.814	4.99	3.8	0.806	3.7
	Uncorrected ASHRAE	96	0.826	4.77	5.6	0.807	4.6
	Corrected ASHRAE	96	0.829	5.09	4.8	0.812	4.0
	Theoretical ASHRAE	96	0.814	4.98	4.0	0.805	3.7

* $W/(m^2 \cdot °C)$

Table 5

Possible Measurand Errors in Compliance with ASHRAE 93-77.
Each Assumed to be Equally Probable.

Random No. Internal	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11
Δt_a	- 0.5	- 0.4	- 0.3	- 0.2	- 0.1	0	0.1	0.2	0.3	0.4	0.5
ΔI $630\ W/m^2$	-18.9	-15.1	-11.3	- 7.6	- 3.8	0	3.8	7.6	11.3	15.1	18.9
ΔI $1000\ W/m^2$	-30.0	-24.0	-18.0	-12.0	- 6.0	0	6.0	12.0	18.0	24.0	30.0
$\Delta t_{f,i}$	- 0.5	- 0.4	- 0.3	- 0.2	- 0.1	0	0.1	0.2	0.3	0.4	0.5
$\Delta\Delta t_f$	- 0.1	- 0.08	- 0.06	- 0.04	- 0.02	0	0.02	0.04	0.06	0.08	0.1
$\Delta\dot{m}\ x10^4$	- 3.58	- 2.86	- 2.15	- 1.43	- 0.72	0	0.72	1.43	2.15	2.86	3.58
ΔA	- 0.0179	- 0.0143	- 0.0107	-0.0072	-0.0036	0	0.0036	0.0072	0.0107	0.0143	0.0179

Based on $\dot{m} = 0.0358$ kg/s, $A = 1.79\ m^2$ and $I = 1000\ W/m^2$ or $630\ W/m^2$.

Table 6

Randomly Selected Errors (from Table 5) Associated with Each Measurand for the 10 Hypothetical Test Facilities

Test Facility	Δt_{a_j} °C	ΔI_j 1000 W/m^2	ΔI_j 630 W/m^2	$\Delta t_{f,i_j}$ °C	$\Delta \Delta t_{f_j}$ °C	$\Delta \dot{m}_j$ kg/s	ΔA_j m^2
1	-0.5	- 6	- 3.8	0.4	-0.08	2.15×10^{-4}	1.79×10^{-2}
2	0.2	- 6	- 3.8	0.5	0	-0.72	1.07
3	-0.2	18	11.3	-0.2	-0.06	-2.86	1.43
4	0.3	-30	-18.9	-0.3	0.08	0	-1.07
5	-0.2	30	18.9	0.5	0.02	-0.72	0.36
6	-0.2	24	15.1	0.3	0.08	-0.72	1.43
7	-0.1	- 6	- 3.8	-0.4	0.06	-2.86	-1.79
8	-0.5	0	0	-0.4	0.04	0.72	-1.79
9	0.5	0	0	0.2	0.04	-1.43	0.36
10	0.3	12	7.6	-0.1	0.02	0.72	1.79

Table 7

Yearly Fraction for a Residential Space Heating and Domestic Hot Water System in Madison, Wisconsin

	COLLECTOR TEST RESULTS				SYSTEM PERFORMANCE	
Description	$F'(\tau\alpha)_e$	Percent Deviation %	$F'U_L$ $W/(m^2 \cdot °C)$	Percent Deviation %	Yearly Solar Fraction	Percent Deviation %
Mean	0.76	-	6.58	-	52.8	-
Best $F'U_L$	0.83	+9.2	5.20	-2.09	63.1	+20.0
Best $F'(\tau\alpha)_e$	0.87	+14.5	6.27	-4.7	60.6	+15.0
Worst $F'(\tau\alpha)_e + F'U_L$	0.67	-11.8	8.50	+29.2	41.0	-23.0

Table 8

Effect of Collector Variance on Yearly Solar Fraction
for a Residential Solar Domestic Hot Water System

			Yearly Solar Fraction, %				
Test Facility	$F_R\ (\tau\alpha)_e$	$F_R U_L$ $W/(m^2 \cdot °C)$	Phoenix	Washington, D.C.	Boston	Seattle	Minneapolis
G	0.87	5.51	97.0	70.3	63.2	58.3	67.9
H	0.85	5.18	97.0	70.3	63.1	58.3	67.7
N	0.86	5.01	97.5	71.8	64.6	59.7	69.1
J	0.83	4.50	97.5	71.9	64.6	59.7	68.8
U	0.85	4.31	98.1	74.3	66.8	61.8	70.9
R	0.85	3.80	98.6	76.8	69.5	63.9	72.9

Average annual water supply temperature		
	Phoenix	15°C
	Washington, D.C.	15°C
	Boston	12°C
	Seattle	11°C
	Minneapolis	7°C

Table 9

Effect of Collector Variance on Yearly Solar Fraction for a Residential Solar Domestic Hot Water System

Test Facility	$F_R (\tau\alpha)_e$	$F_R U_L$ W/(m^2·°C)	Yearly Solar Fraction, % Phoenix	Washington, D.C.	Boston	Seattle	Minneapolis
M	0.85	6.26	95.5	65.7	58.8	54.2	63.9
G	0.87	5.51	97	70.3	63.2	58.3	67.9
Q	0.85	5.50	96.5	68.9	61.8	57.0	66.5
A	0.86	5.32	97.0	70.4	63.2	58.3	67.8
H	0.85	5.18	97.0	70.3	63.1	58.3	67.7
D	0.85	3.90	98.5	76.3	68.5	63.5	72.5
R	0.85	3.80	98.6	76.8	69.5	63.9	72.9
L	0.88	3.77	99.1	79.3	71.4	66.2	75.3
B	0.80	3.05	98.6	76.8	68.7	63.7	72.1
I	0.89	3.02	99.9	83.5	75.6	69.9	79.0

Average annual supply temperature		
	Phoenix	15°C
	Washington, D.C.	15°C
	Boston	12°C
	Seattle	11°C
	Minneapolis	7°C

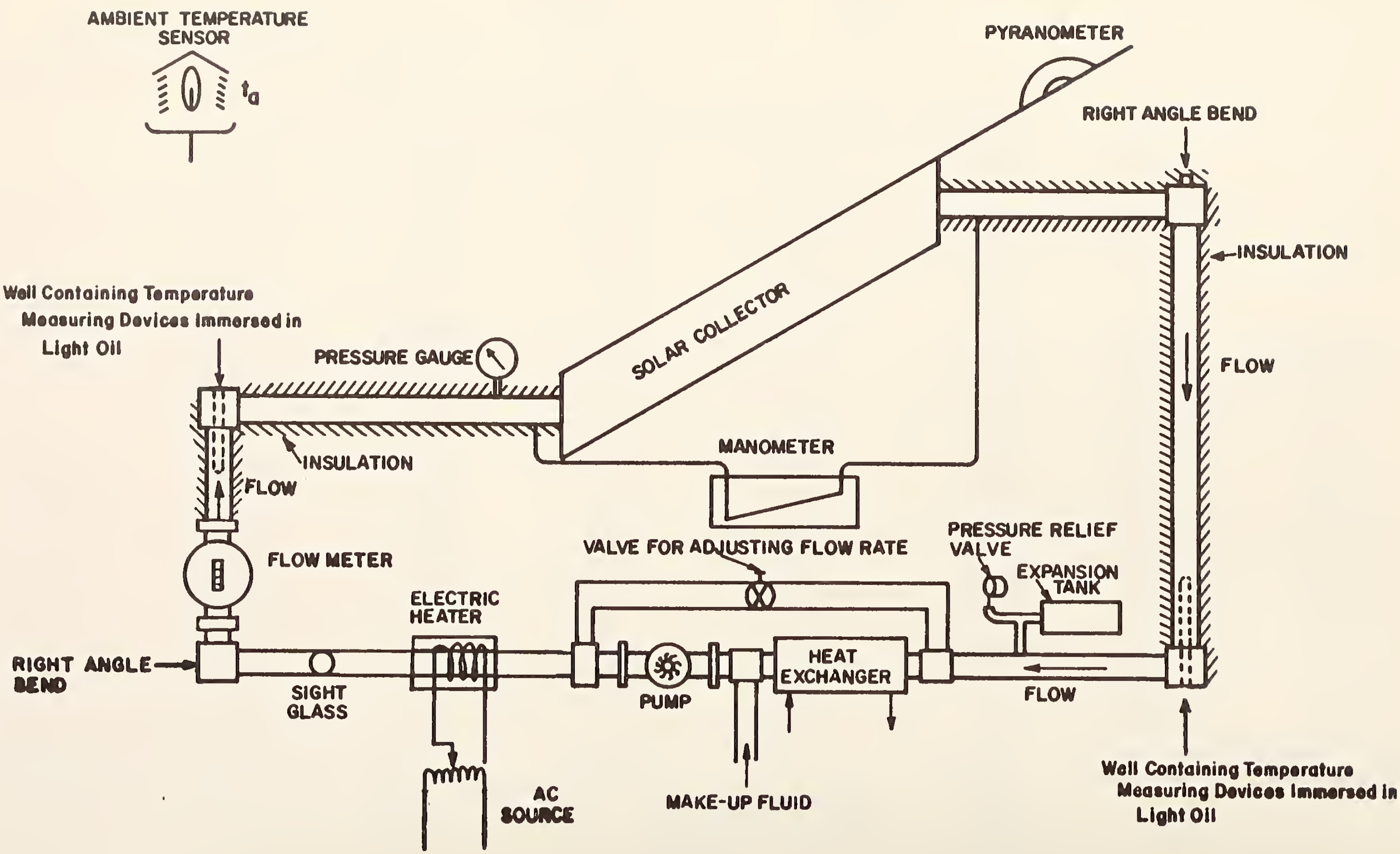


Figure 1 Recommended Testing Configuration for the Solar Collector when the Heat Transfer Fluid is a Liquid [1, 2]

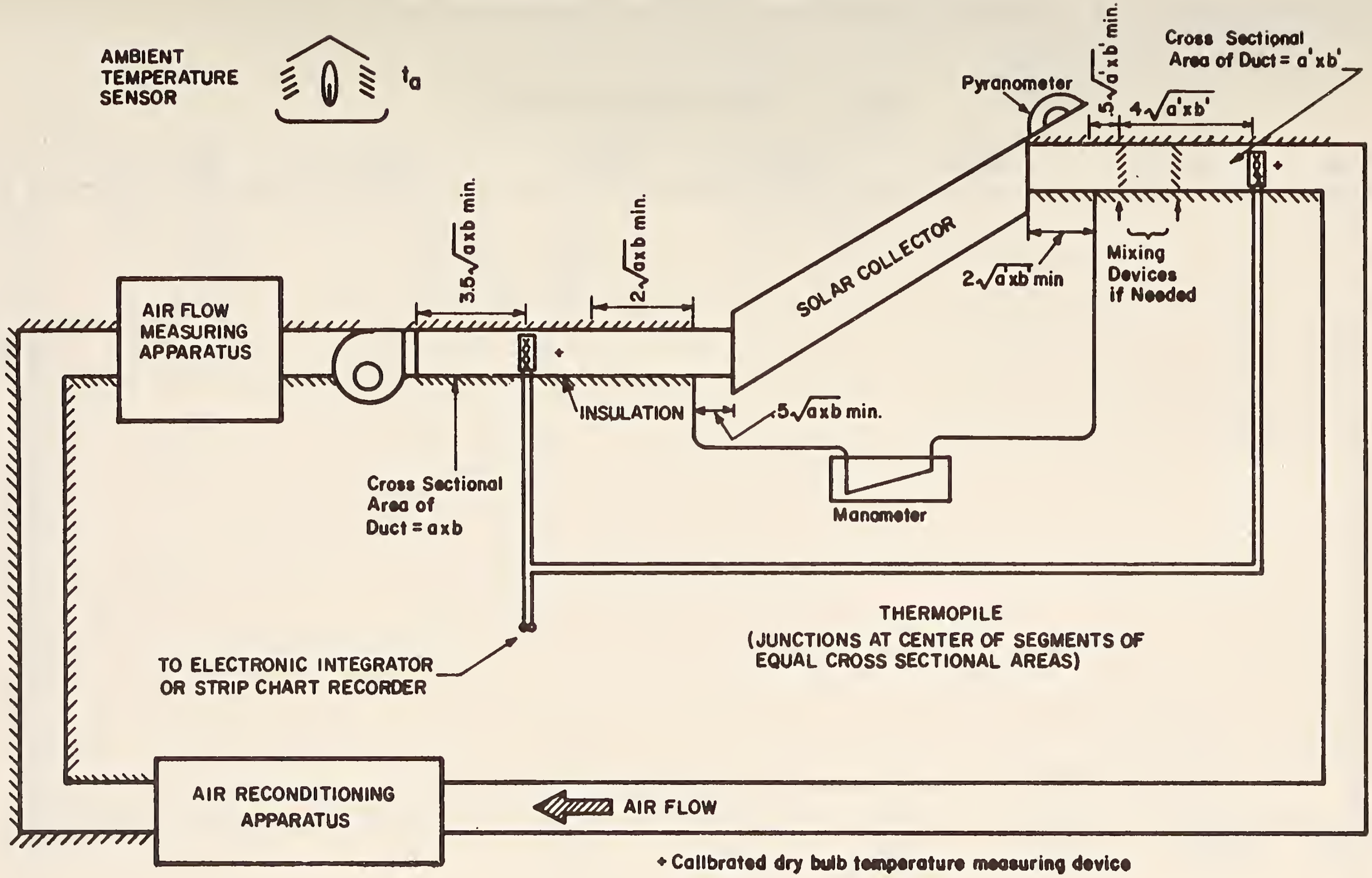


Figure 2 Recommended Testing Configuration for the Solar Collector when the Heat Transfer Fluid is Air [1, 2]

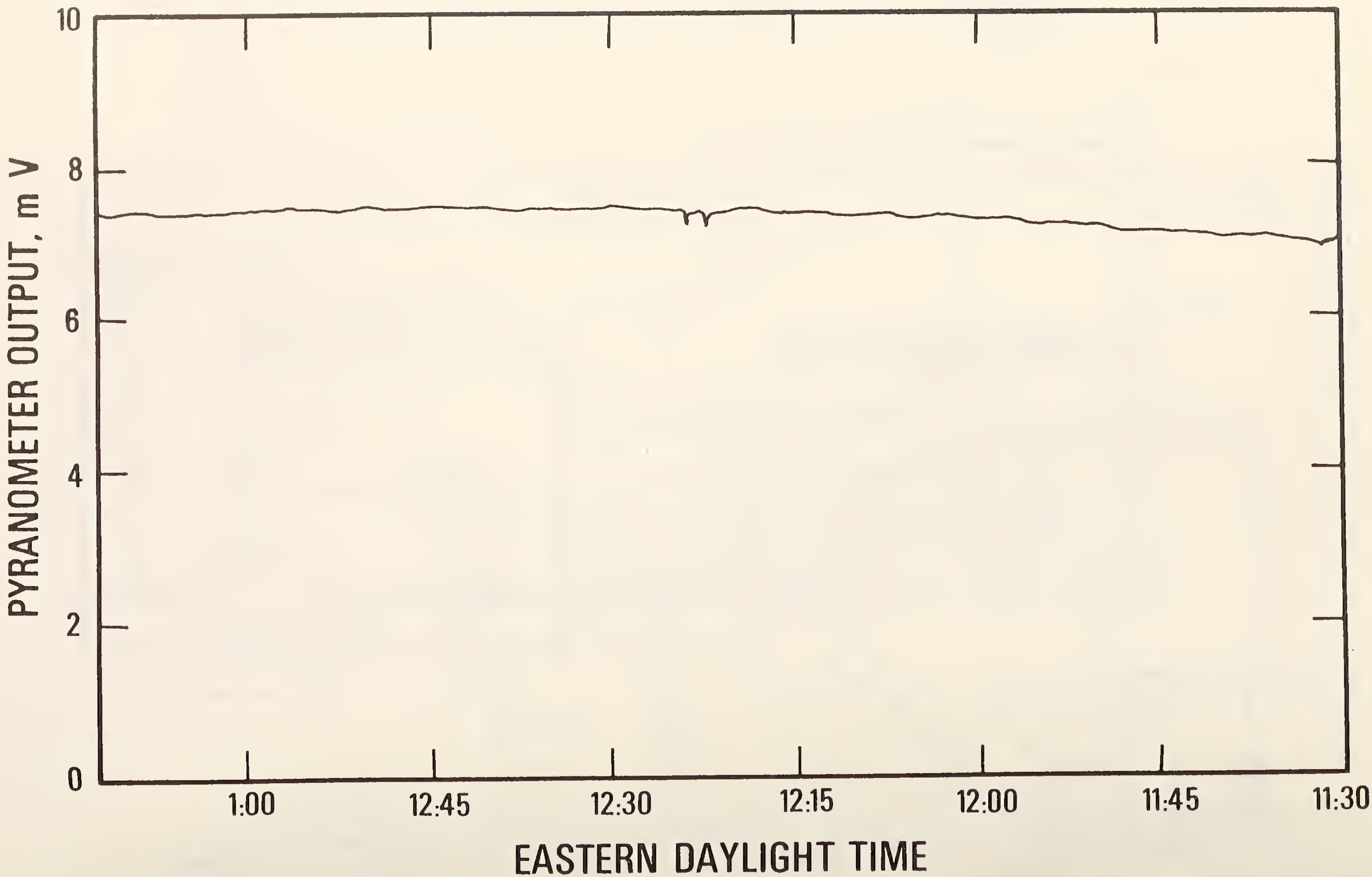


Figure 3 Incident Solar Radiation on a Horizontal Surface in Gaithersburg, Maryland, March 13, 1974 [1, 2]

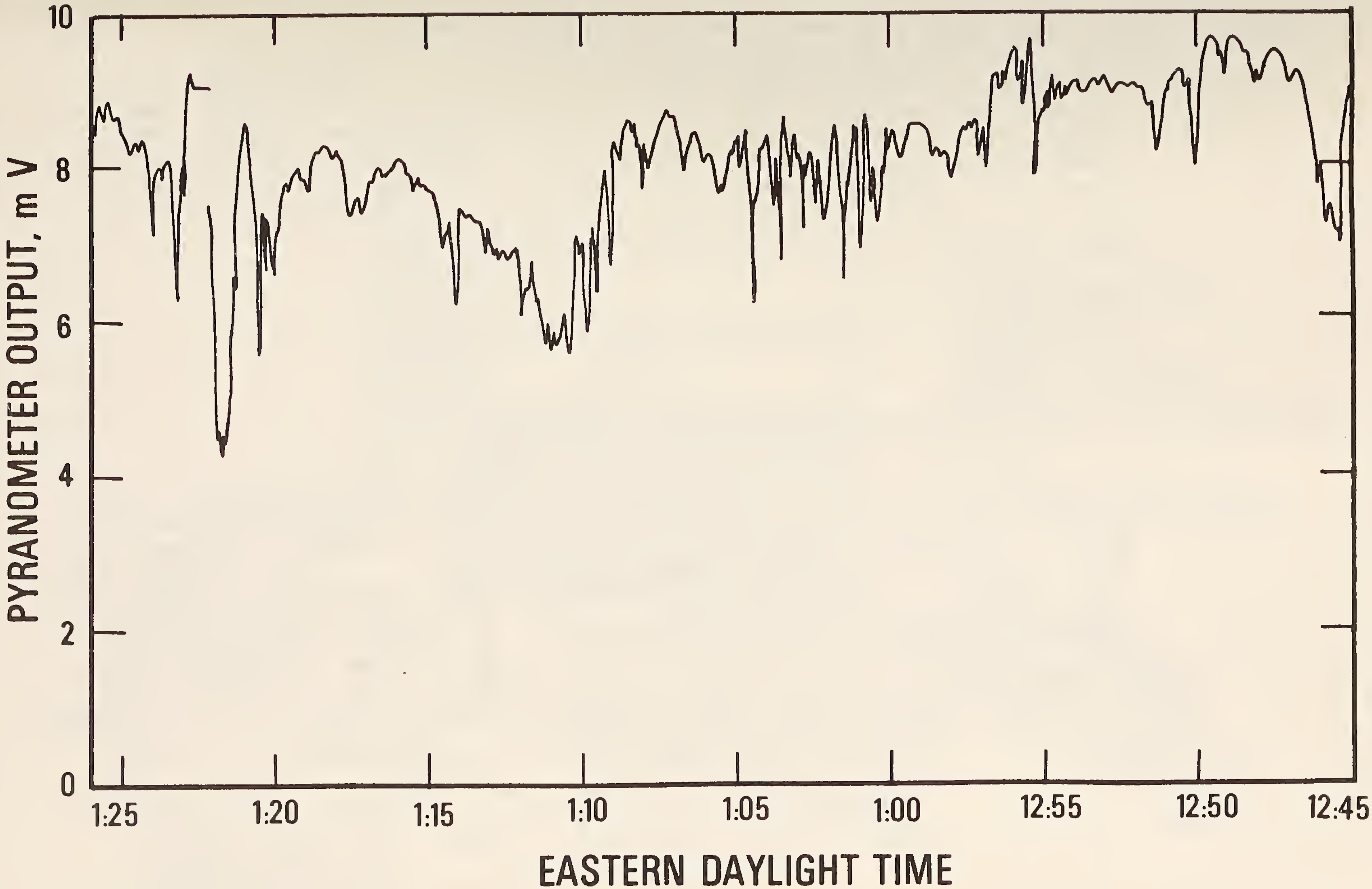
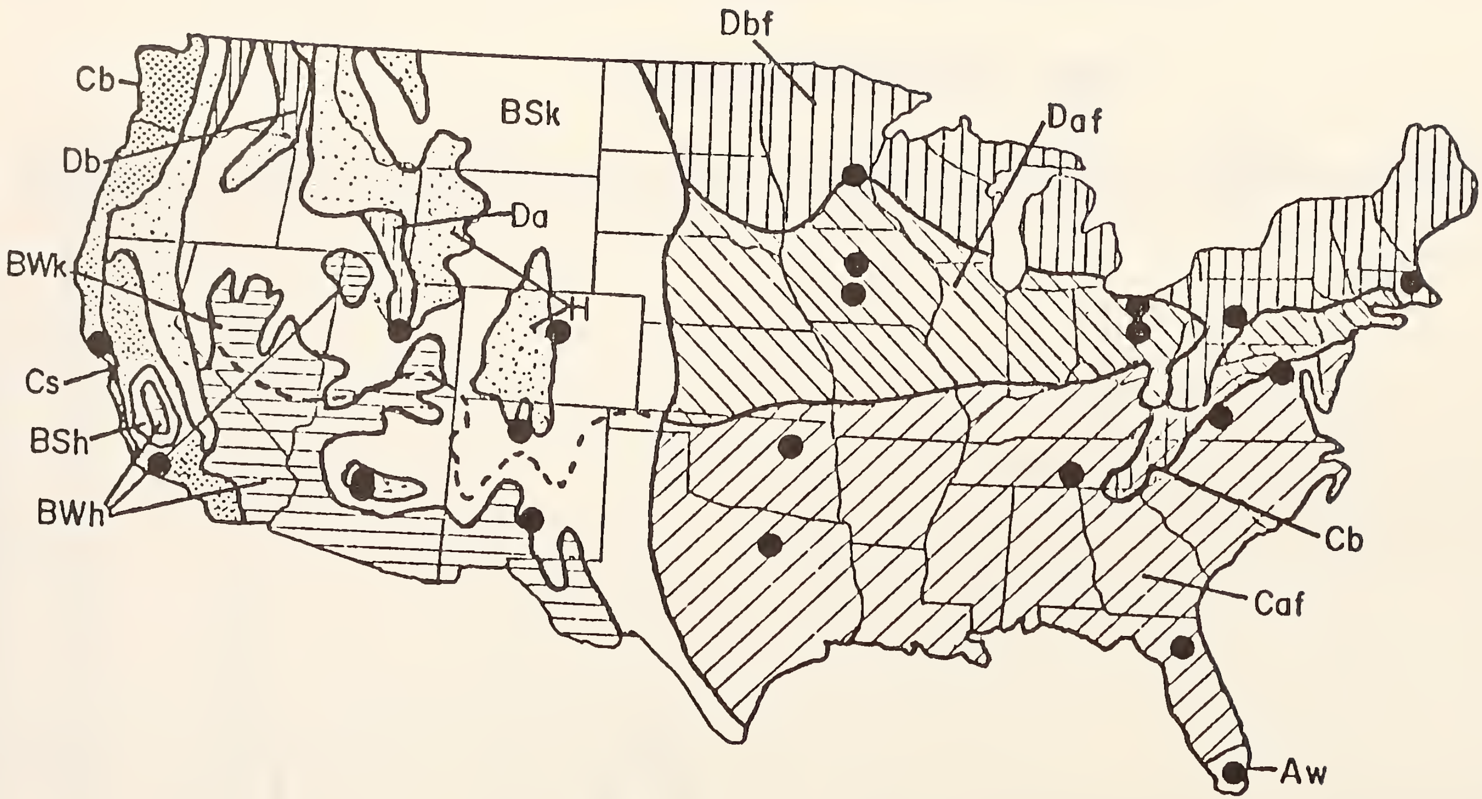


Figure 4 Incident Solar Radiation on a Horizontal Surface in Gaithersburg, Maryland, March 11, 1974 [1, 2]



Aw - Tropical Savanna
BSh - Tropical and Subtropical Steppe
BSk - Middle Latitude Steppe
BWh - Tropical and Subtropical Desert
BWK - Middle Latitude Desert
Cs - Mediterranean

Cb - Marine West Coast
Caf - Humid Subtropical, no dry season
Da - Humid Continental (Warm Summer)
Daf - Humid Continental (Warm Summer), no dry season
Db - Humid Continental (Cool Summer)
Dbf - Humid Continental (Cool Summer), no dry season

Figure 5 Climatic Location of Testing Facilities

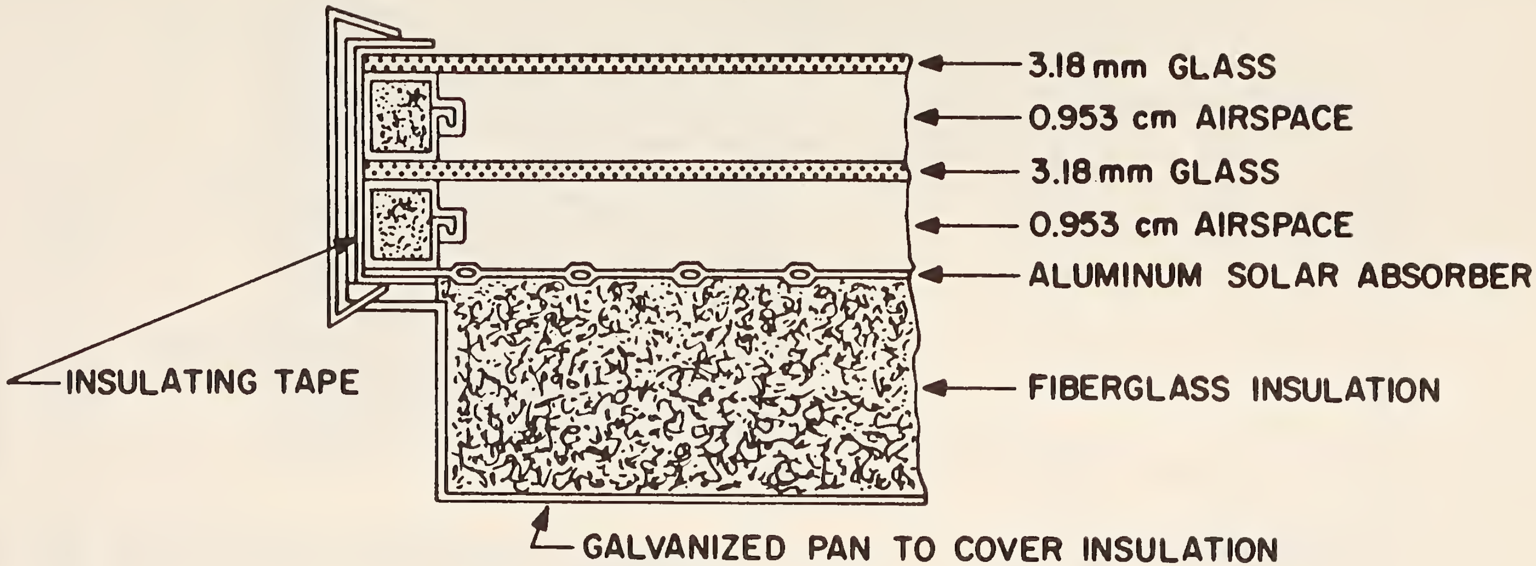


Figure 6 Schematic of Flat-Plate Liquid-Heating Collector No. 1

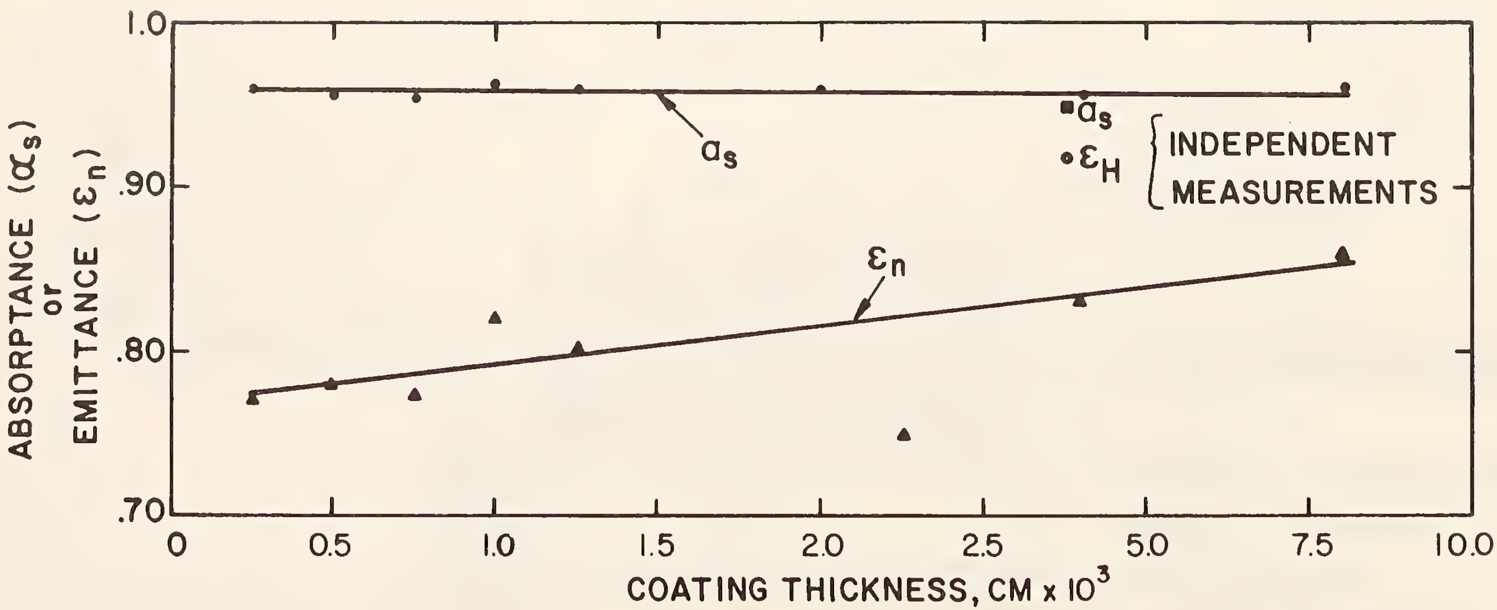
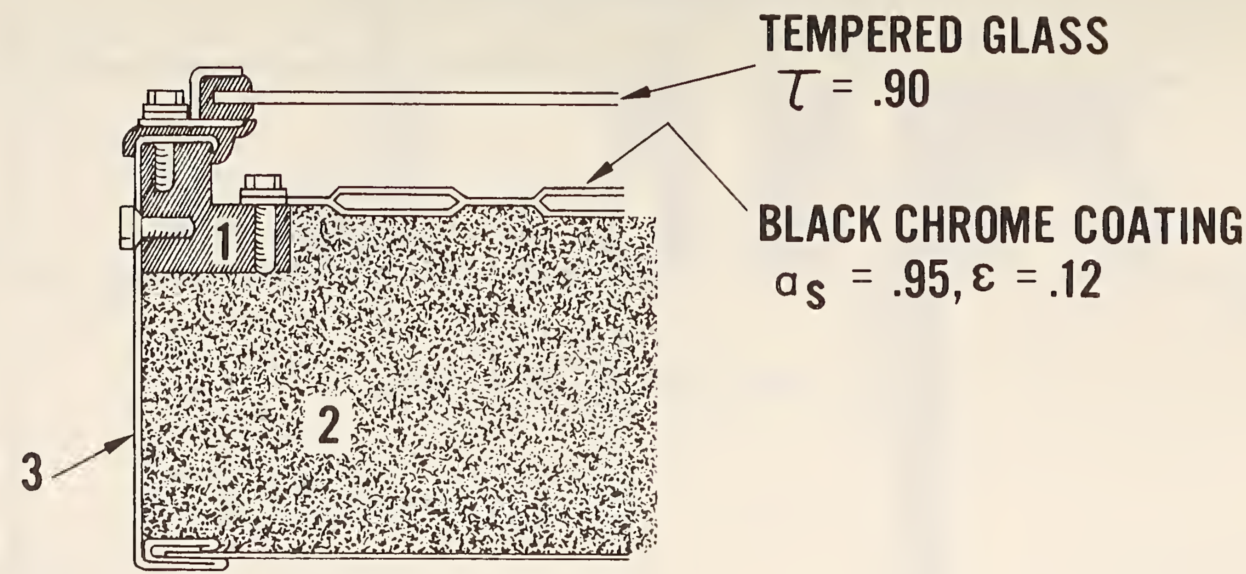


Figure 7 Relationship Between Coating Thickness and Optical Properties for the Absorber Coating of Collector No. 1



1. INSULATING MOUNTING BLOCK
2. FIBERGLASS INSULATION
3. GALVANIZED STEEL COLLECTOR BOX

Figure 8 Schematic of Flat-Plate Liquid-Heating Collector No. 2

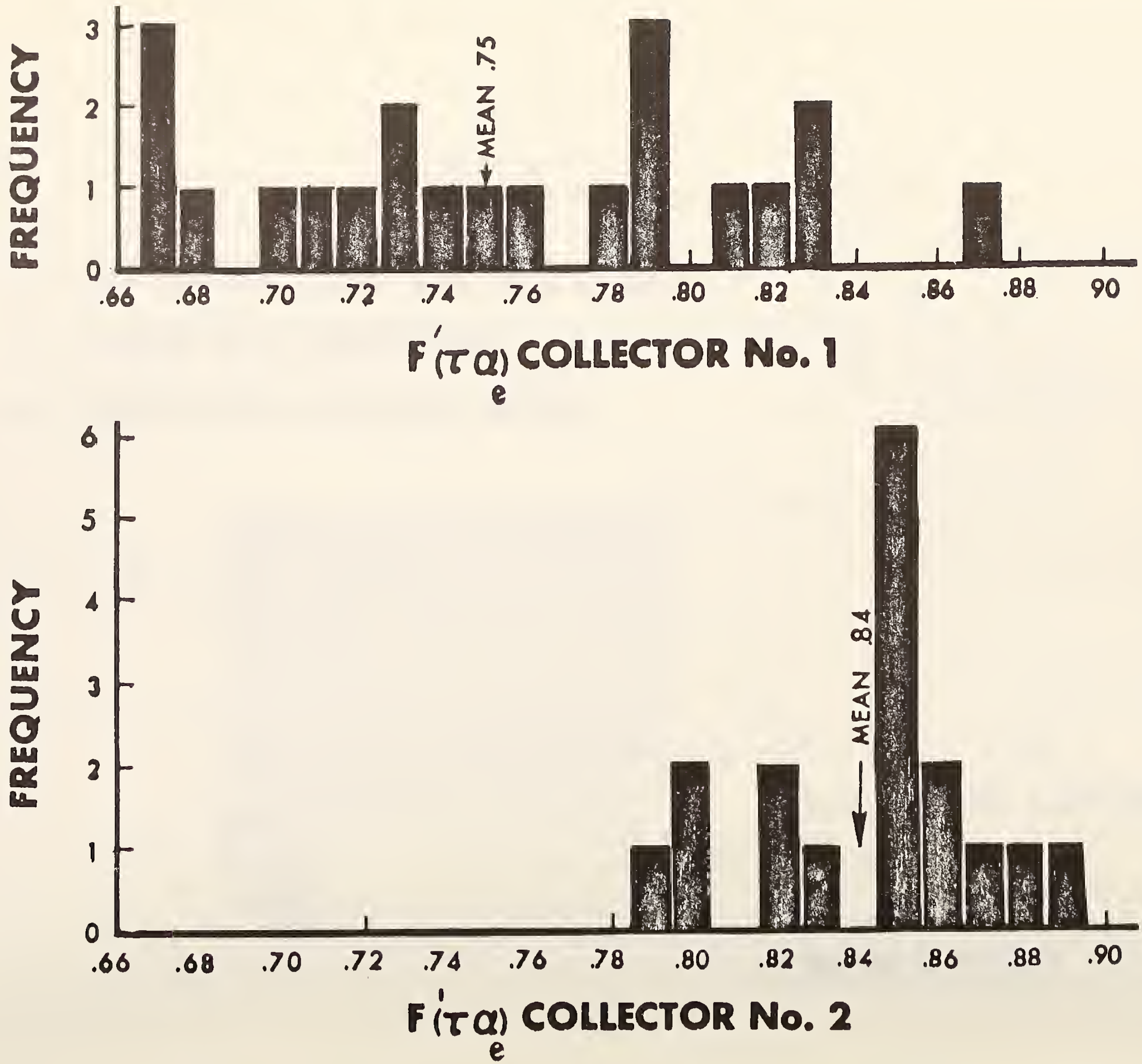


Figure 9 Frequency Distribution of $F'(\tau\alpha)_e$ Values for Round Robin Collectors

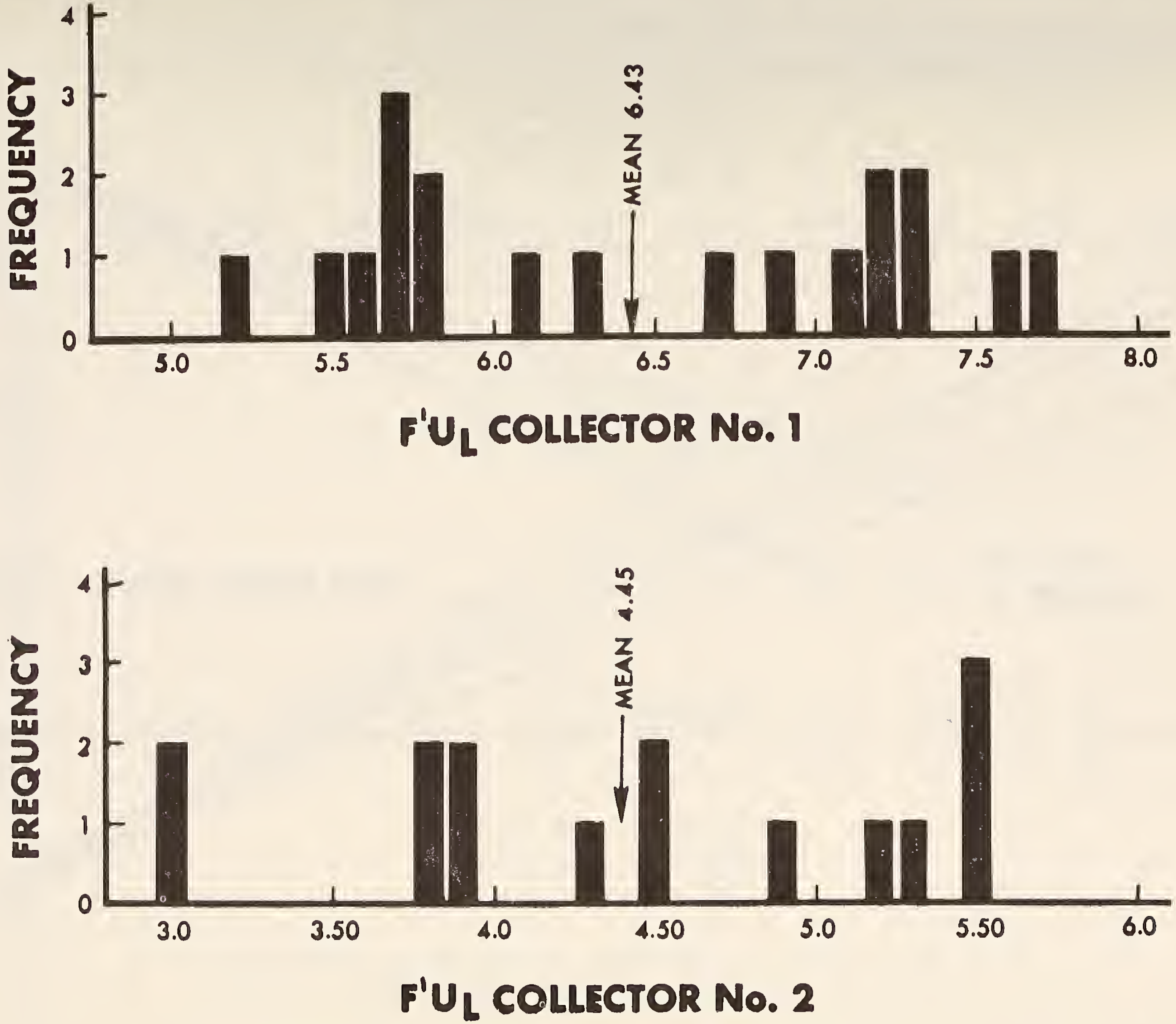


Figure 10 Frequency Distribution of $F'U_L$ Values for Round Robin Collectors

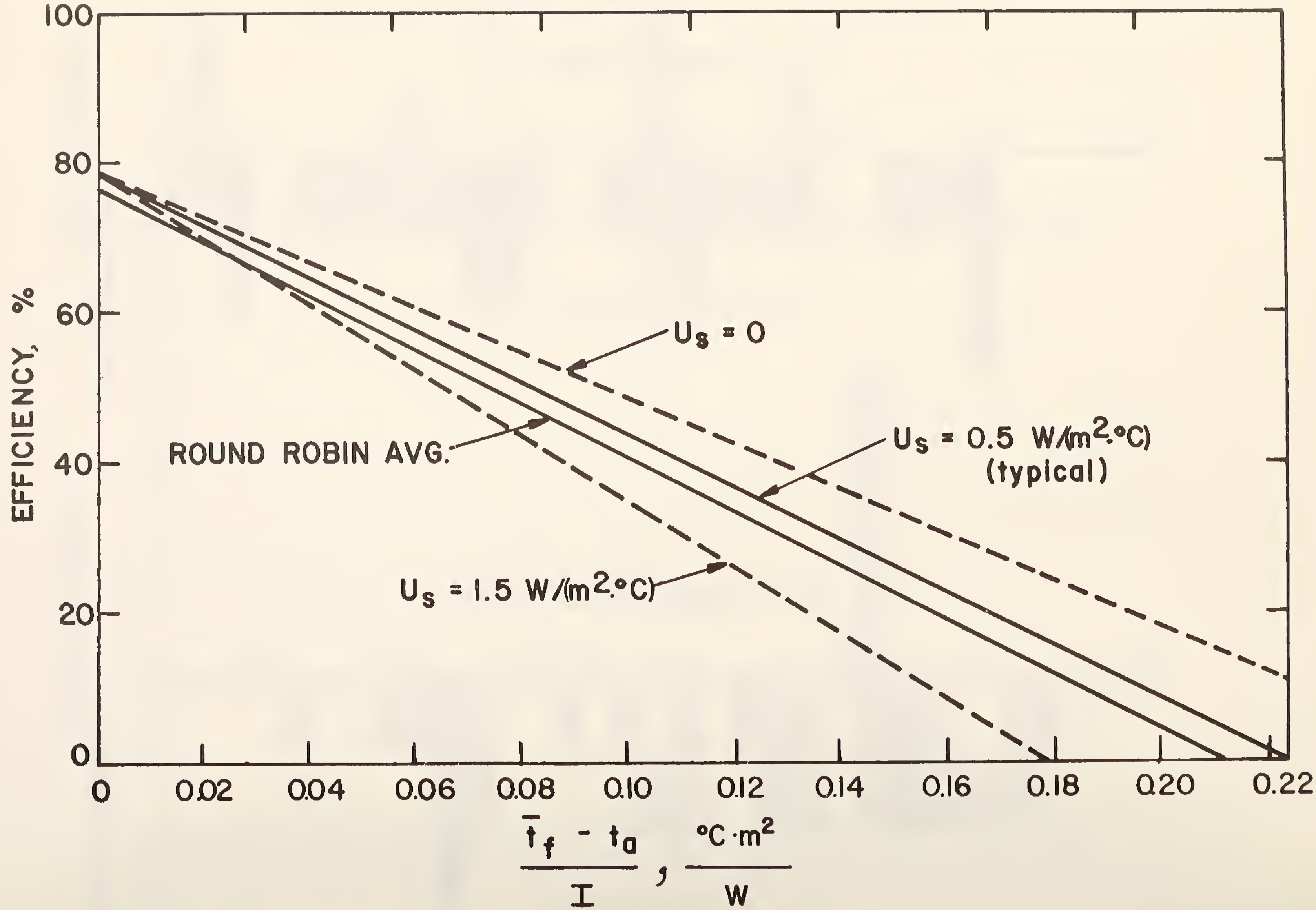


Figure 11 The Influence of Edge Losses on the Overall Loss Coefficient for Collector No. 1

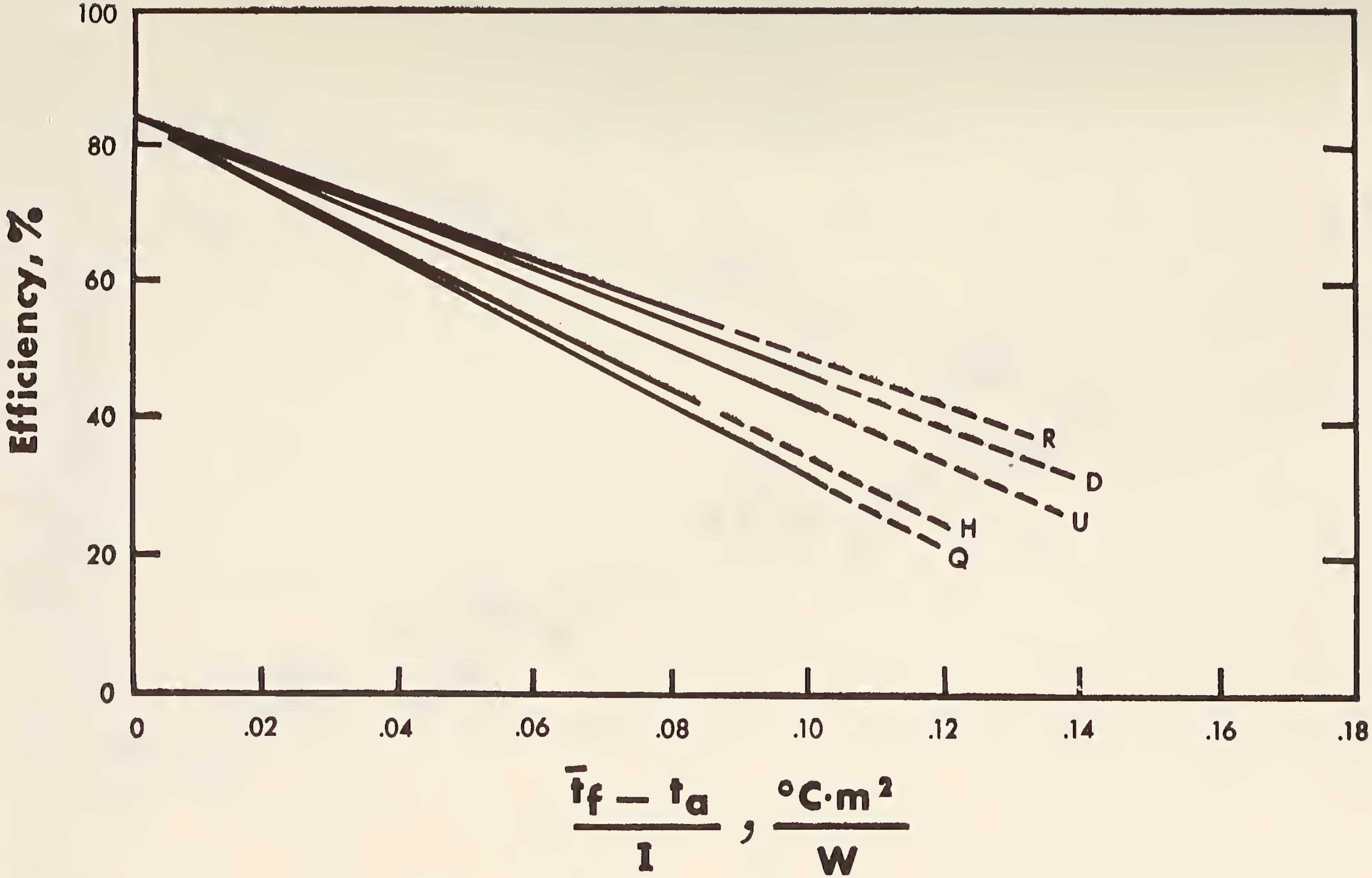


Figure 12 Variation in $F'U_L$ for Collector No. 2 which have Identical $F'(\tau\alpha)_e$

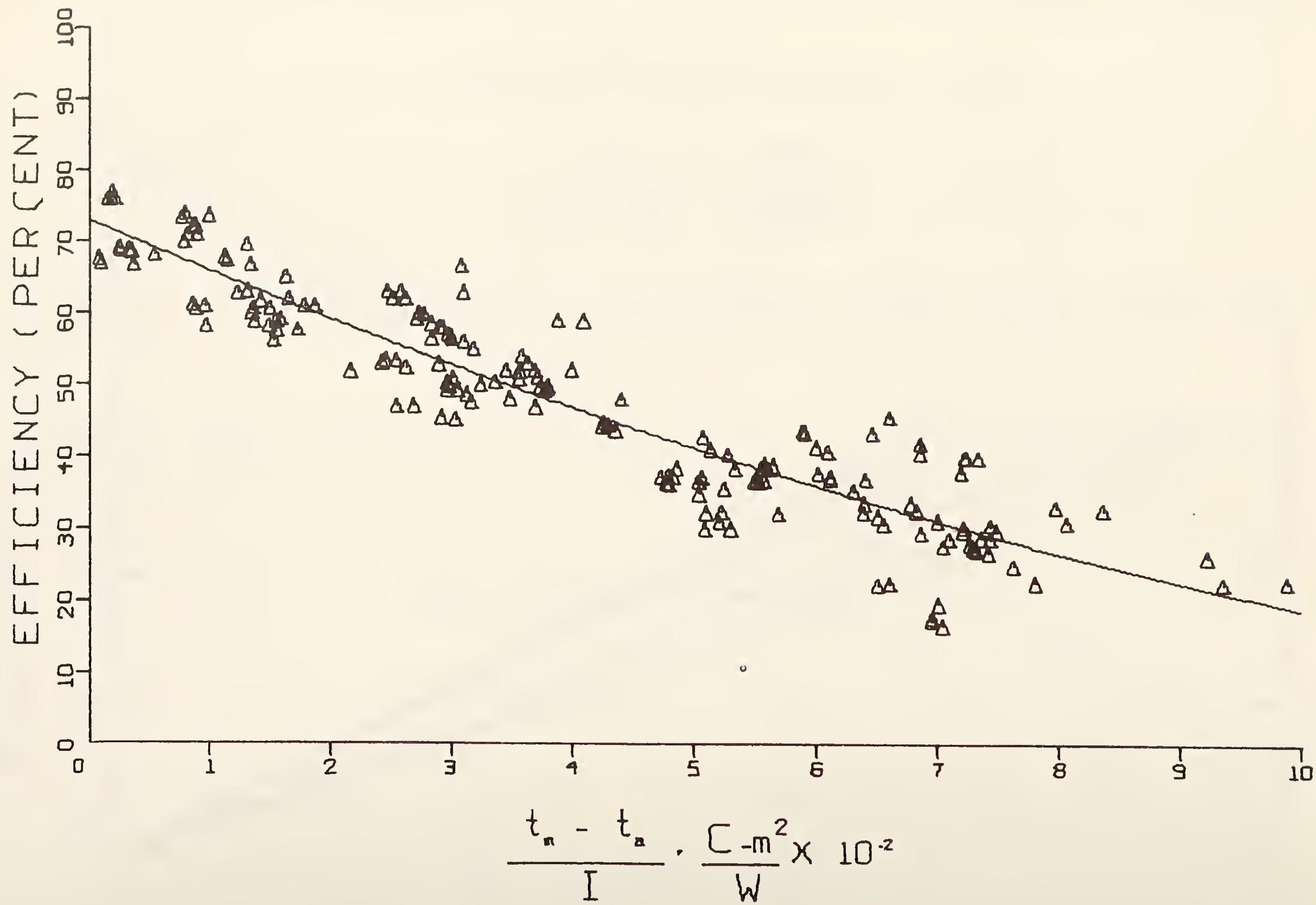


Figure 13 Uncorrected Results from 12 Facilities for Collector No. 1 Tests

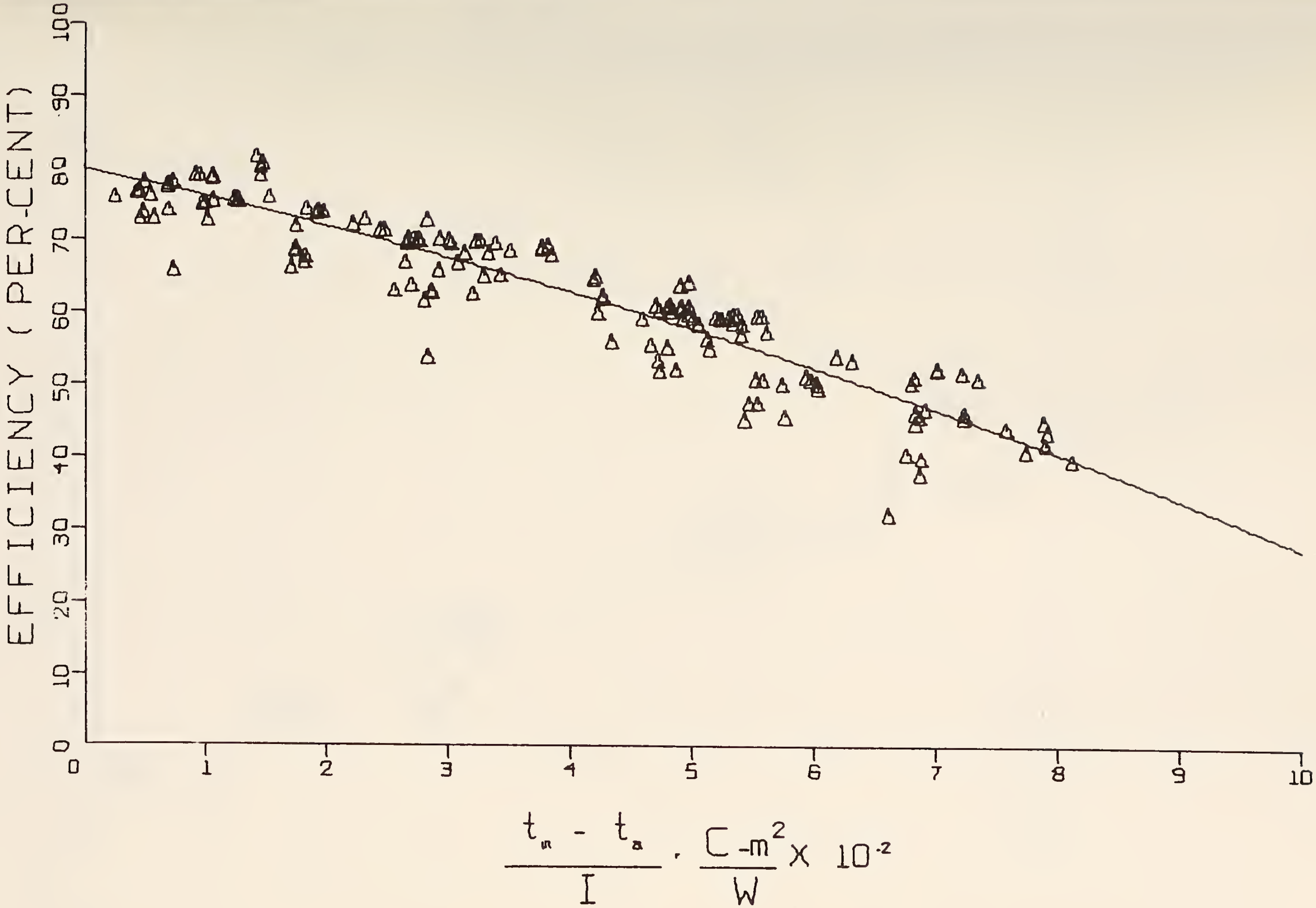


Figure 14 Uncorrected Results from 10 Facilities for Collector No. 2 Tests

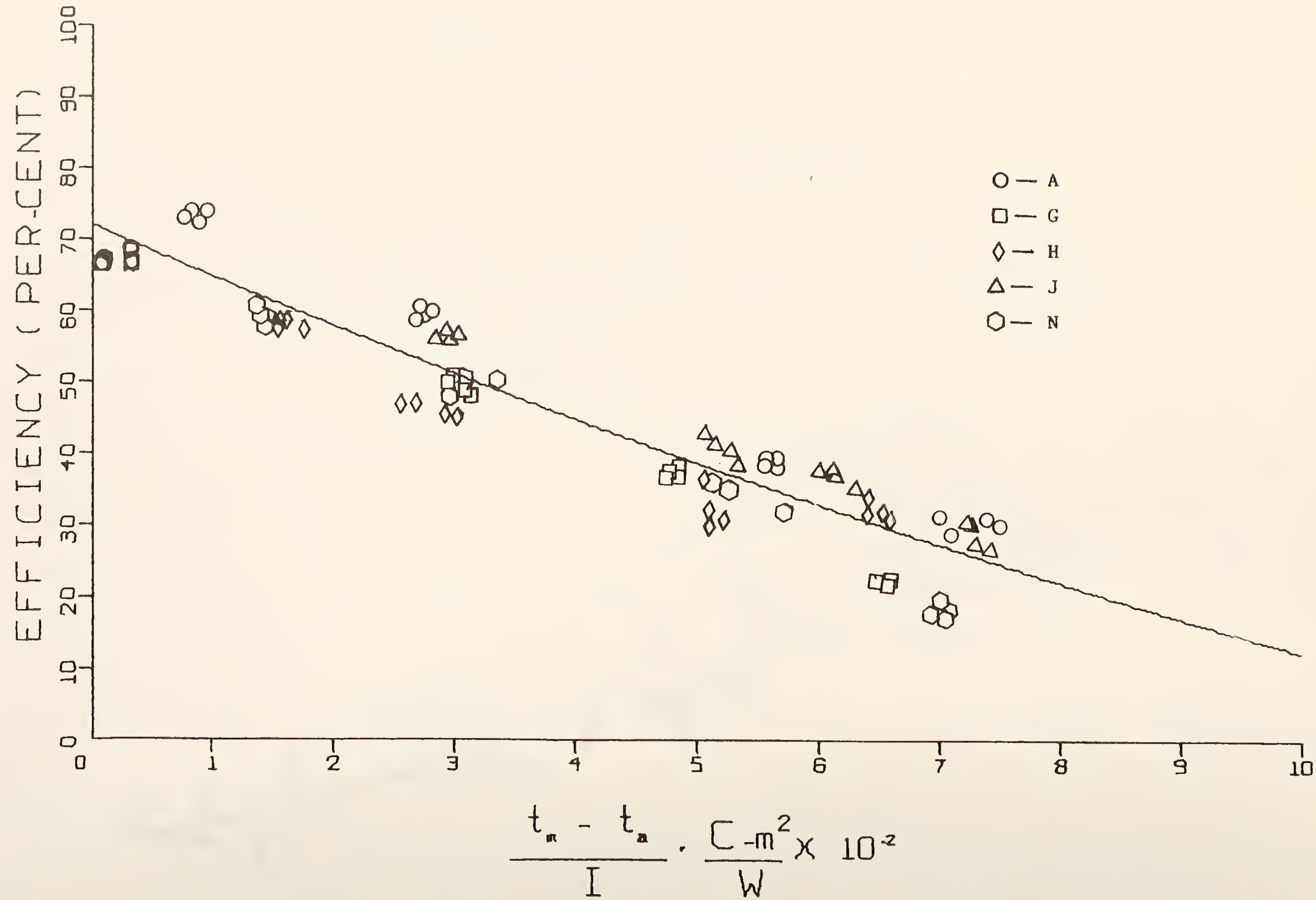


Figure 15 Uncorrected Results from 5 Facilities for the Collector No. 1 Tests Meeting ASHRAE Standard 93-77 Requirements

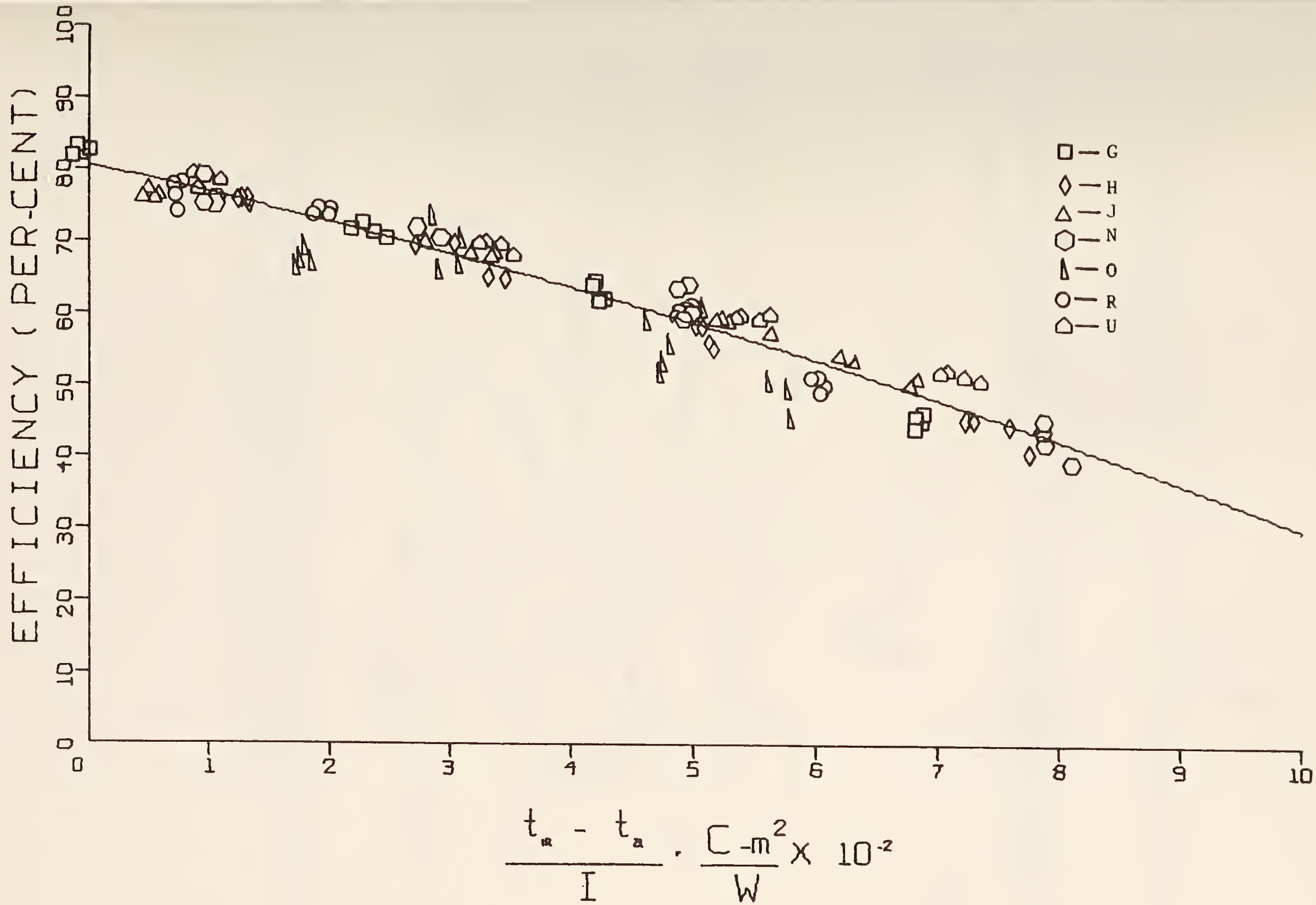


Figure 16 Uncorrected Results from 7 Facilities for the Collector No. 2 Tests Meeting ASHRAE Standard 93-77 Requirements

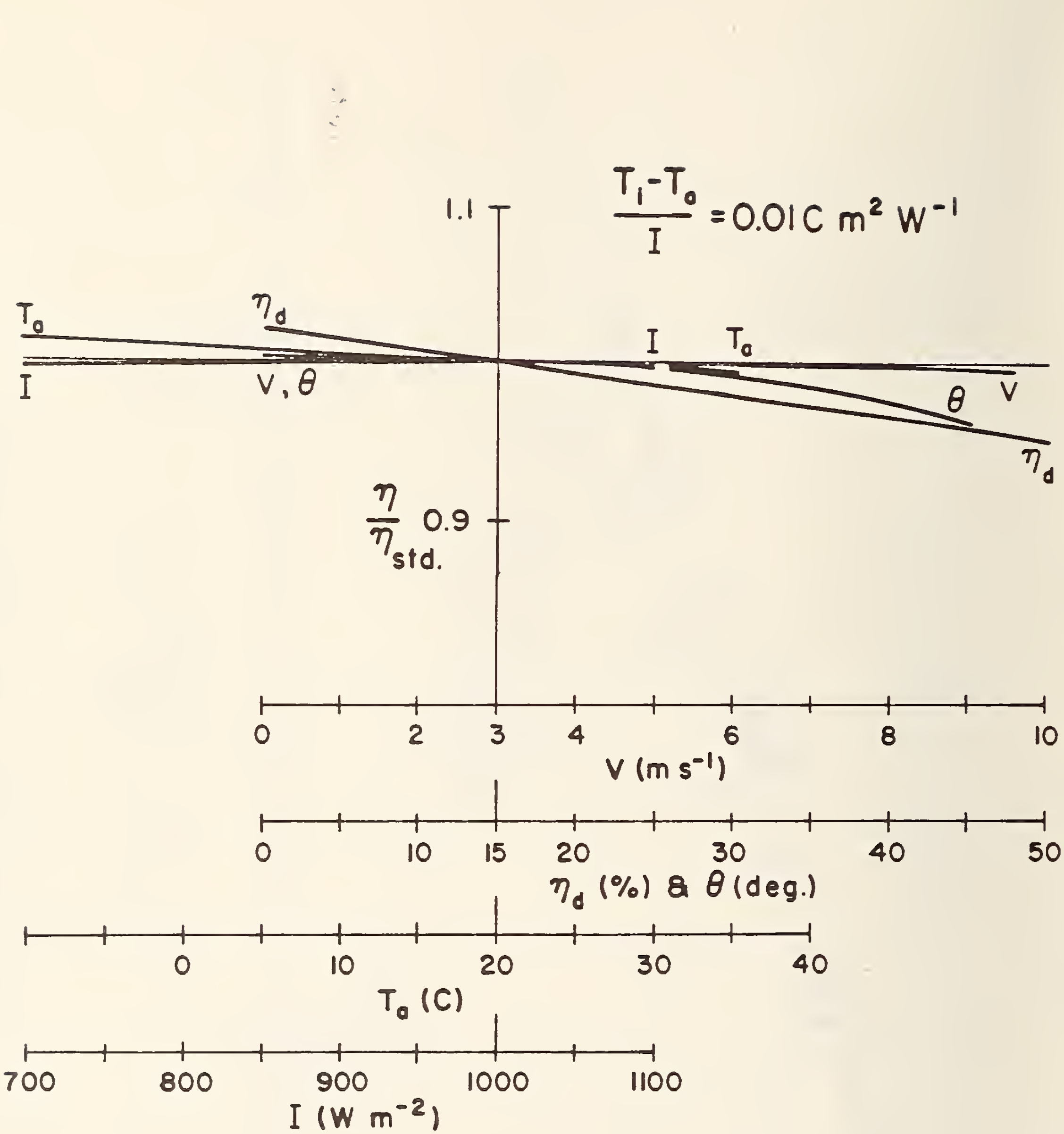


Figure 17 Effect of Environmental Conditions on Efficiency for Collector No. 1 at "Reference" Conditions with $[t_{f,i} - t_a]/I = 0.01$ (°C·m^2)/W

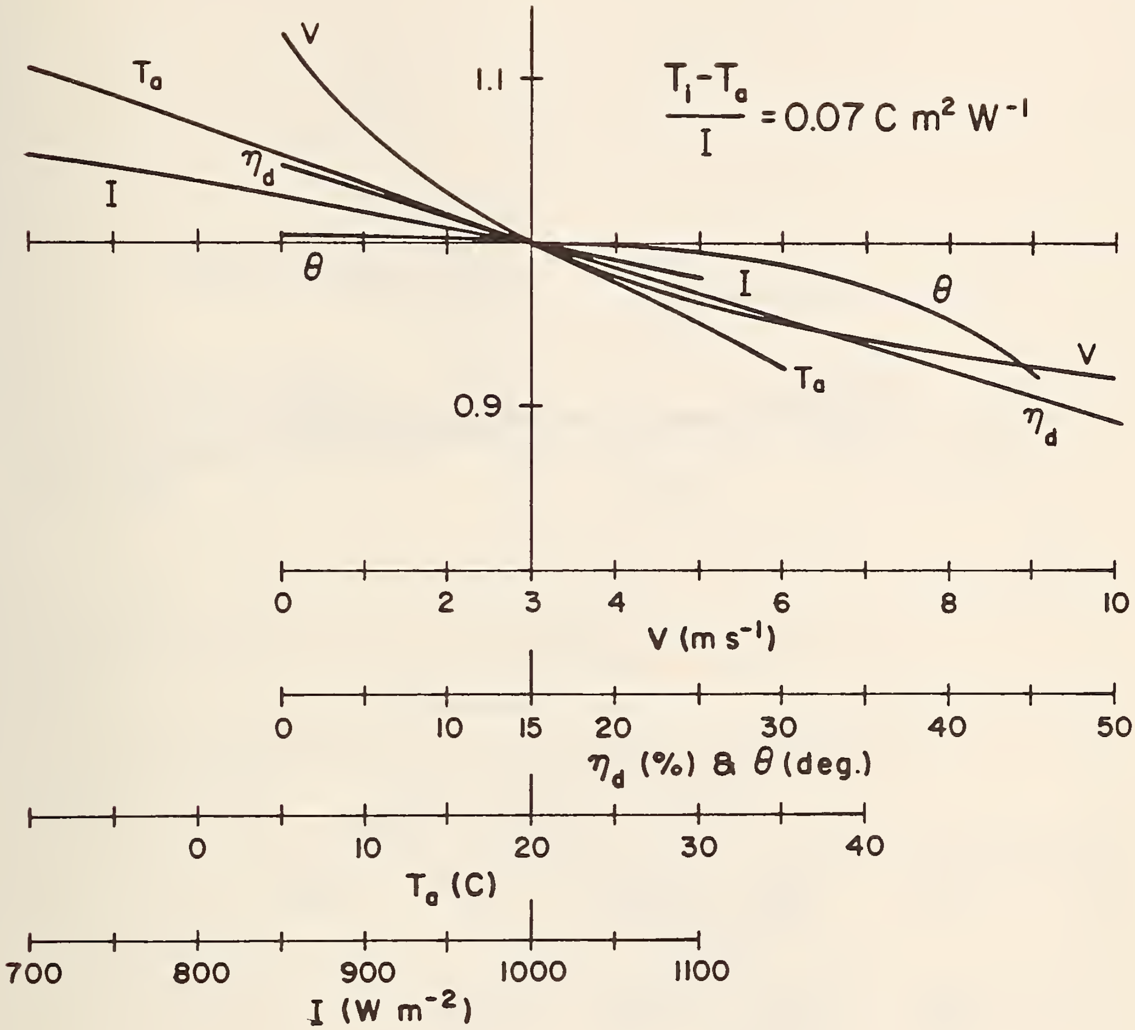


Figure 18 Effect of Environmental Conditions on Efficiency for Collector No. 1 at "Reference" Conditions with $[t_{f,i} - t_a]/I = 0.07$ (°C·m^2)/W

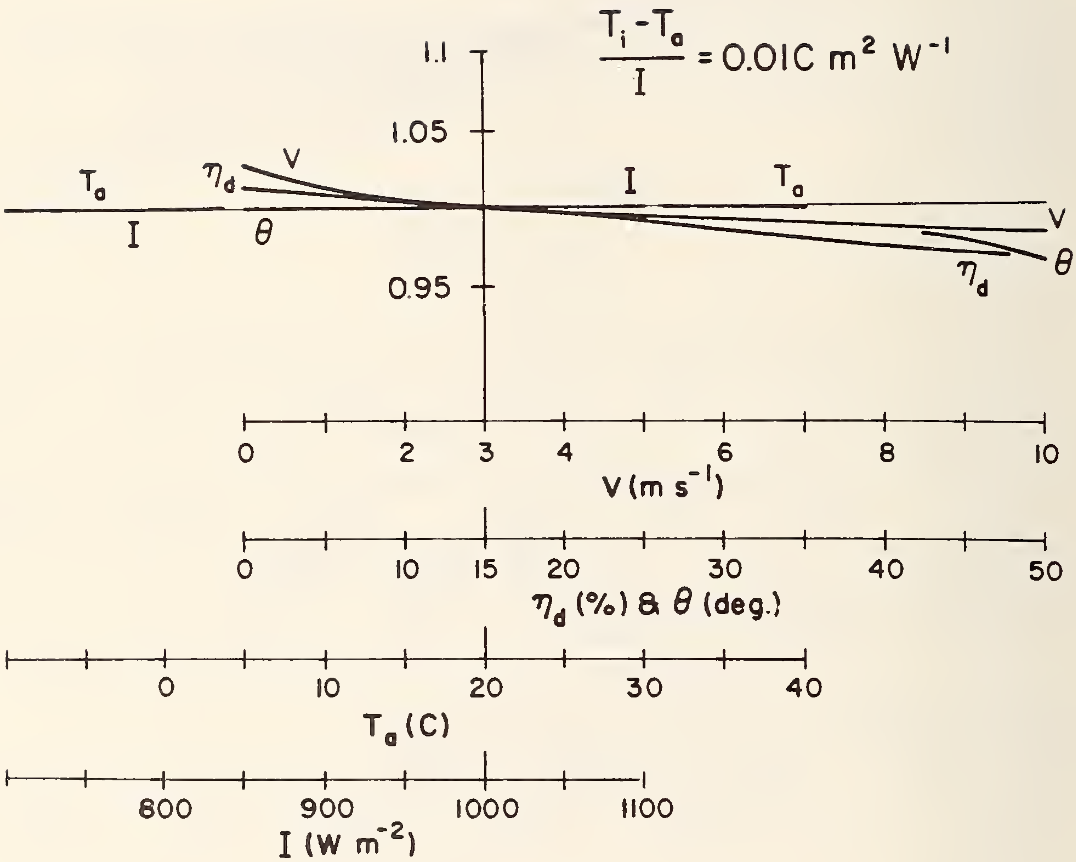


Figure 19 Effect of Environmental Conditions on Efficiency for Collector No. 2 at "Reference" Conditions with $[t_{f,i} - t_a]/I = 0.01\ (°C{\cdot}m^2)/W$

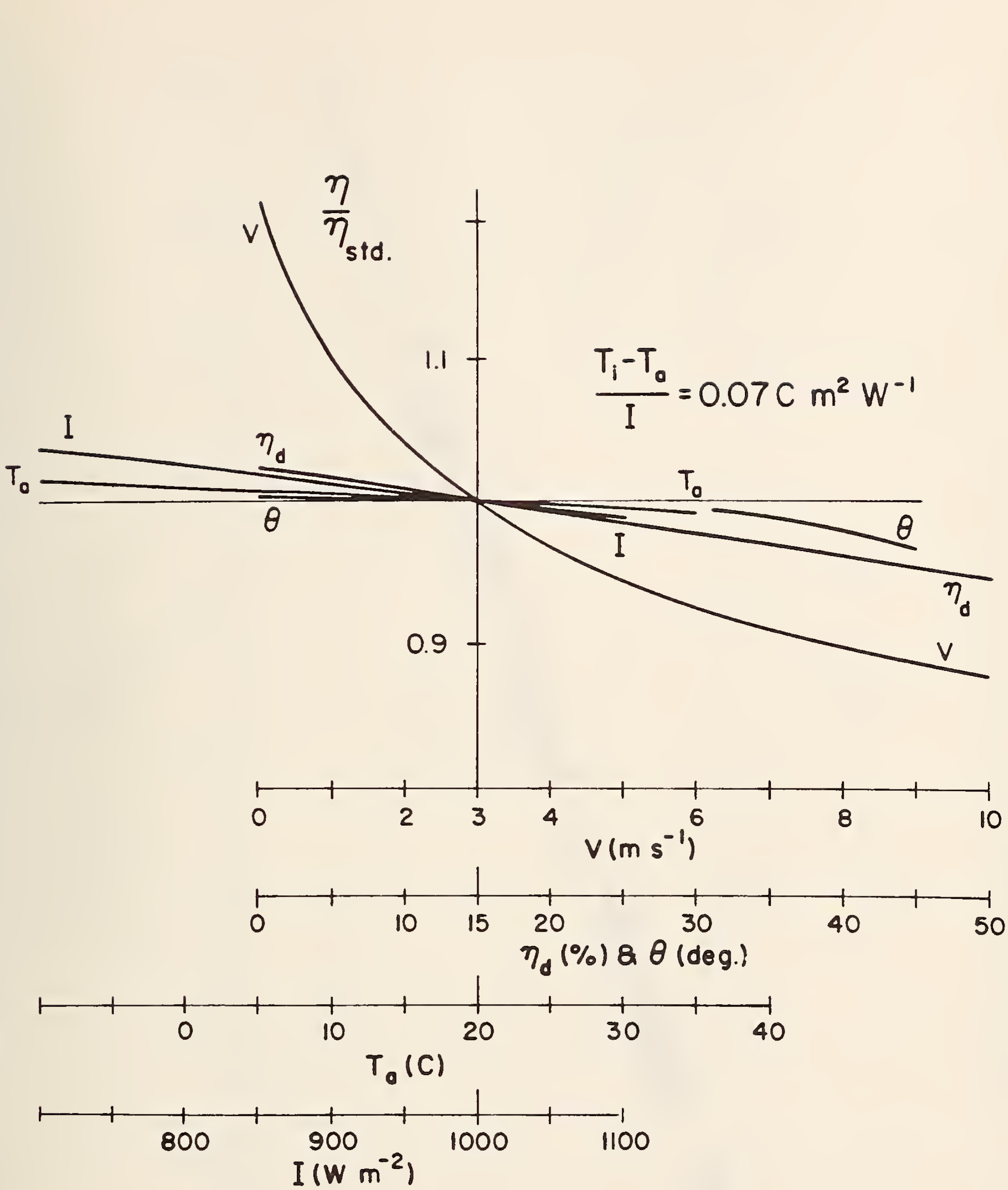


Figure 20 Effect of Environmental Conditions on Efficiency for Collector No. 2 at "Reference" Conditions with $[t_{f,i} - t_a]/I = 0.07$ (°C·m^2)/W

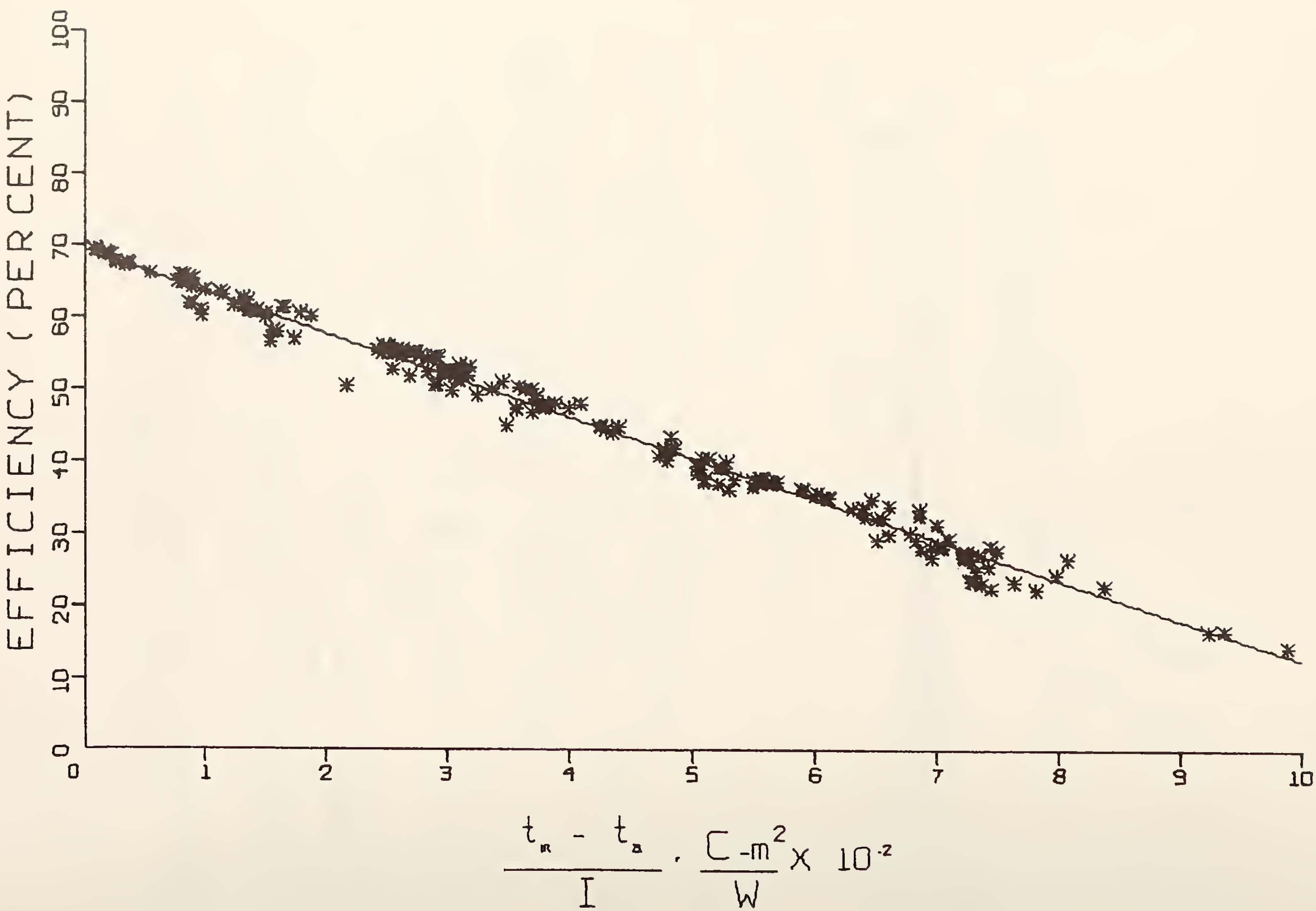


Figure 21 Theoretical Results for Collector No. 1 Based on the Test Conditions Reported by 12 Participants

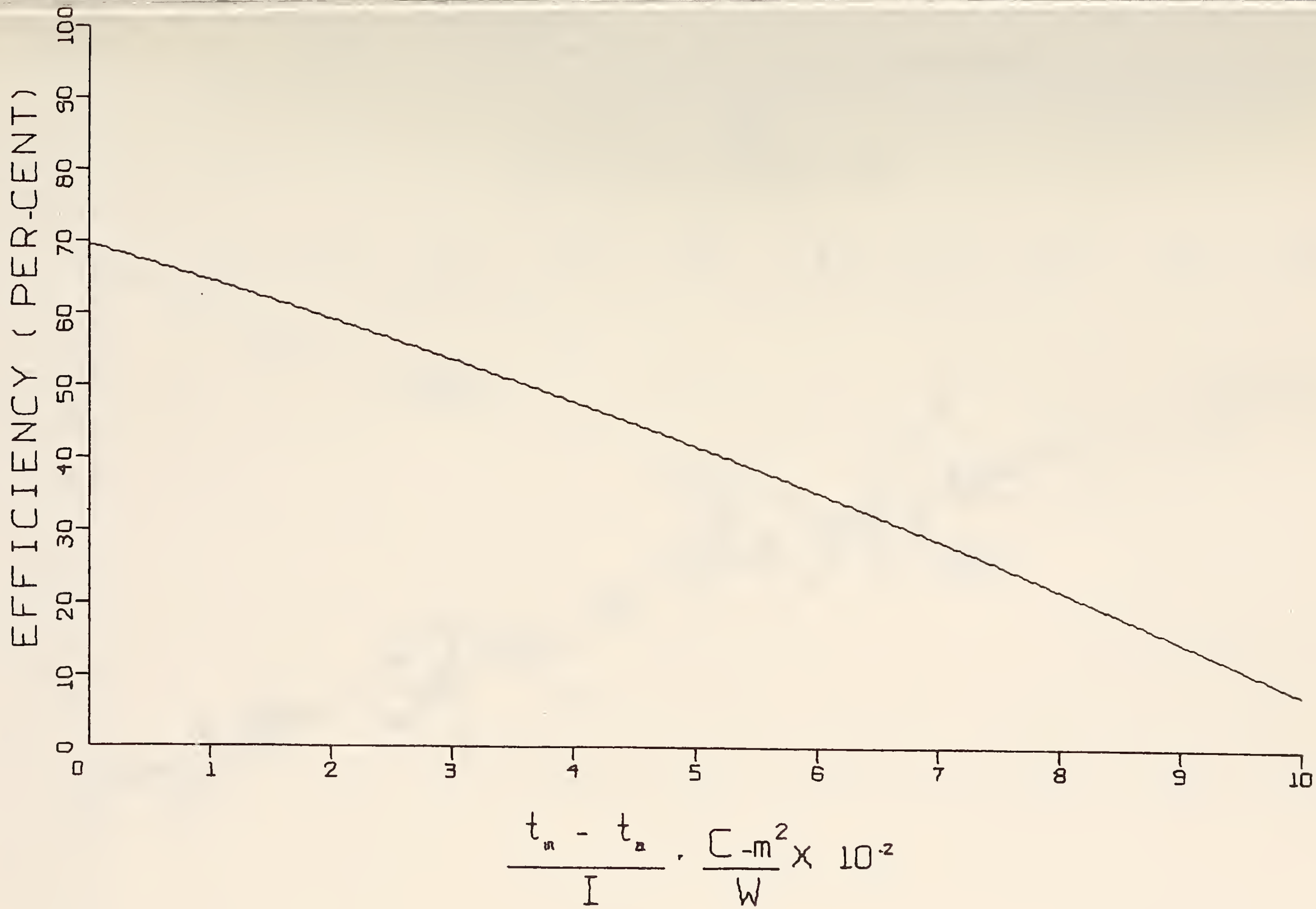


Figure 22 Theoretical Efficiency at "Reference" Conditions for Collector No. 1

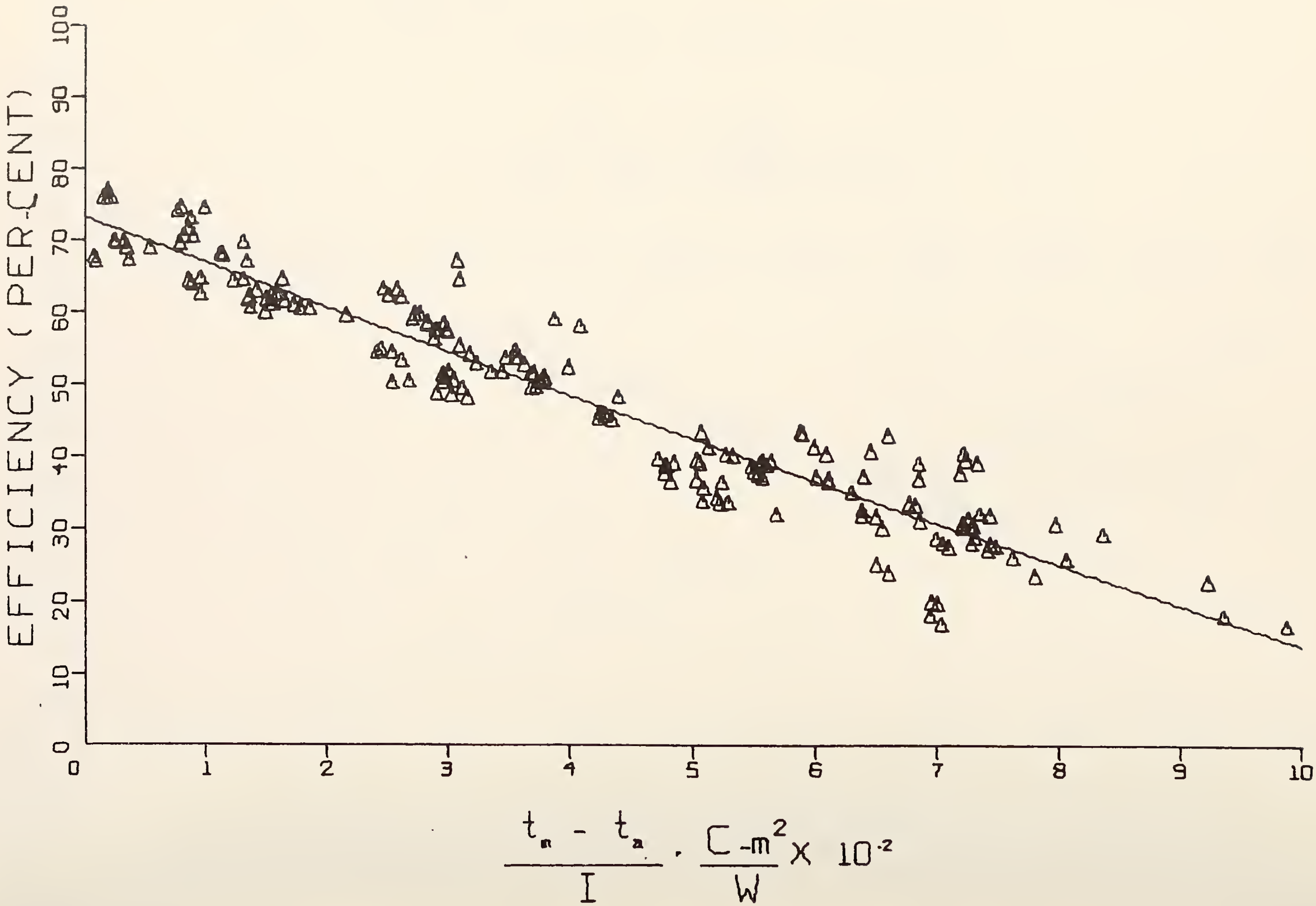


Figure 23 Corrected Results from 12 Facilities for Collector No. 1 Tests

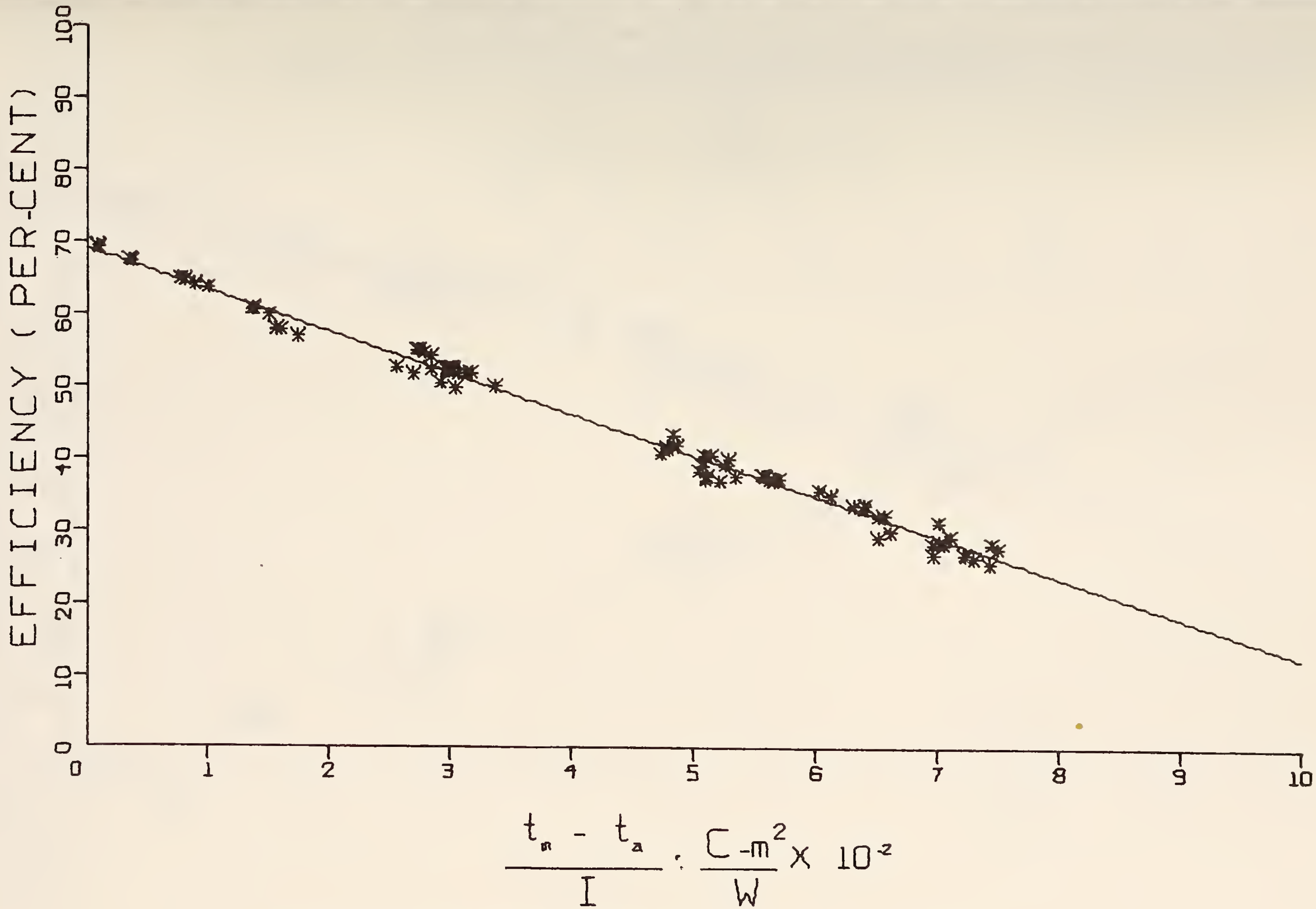


Figure 24 Theoretical Results for Collector No. 1 Based on Test Conditions Meeting ASHRAE Standard 93-77 Requirements Reported by 5 Participants

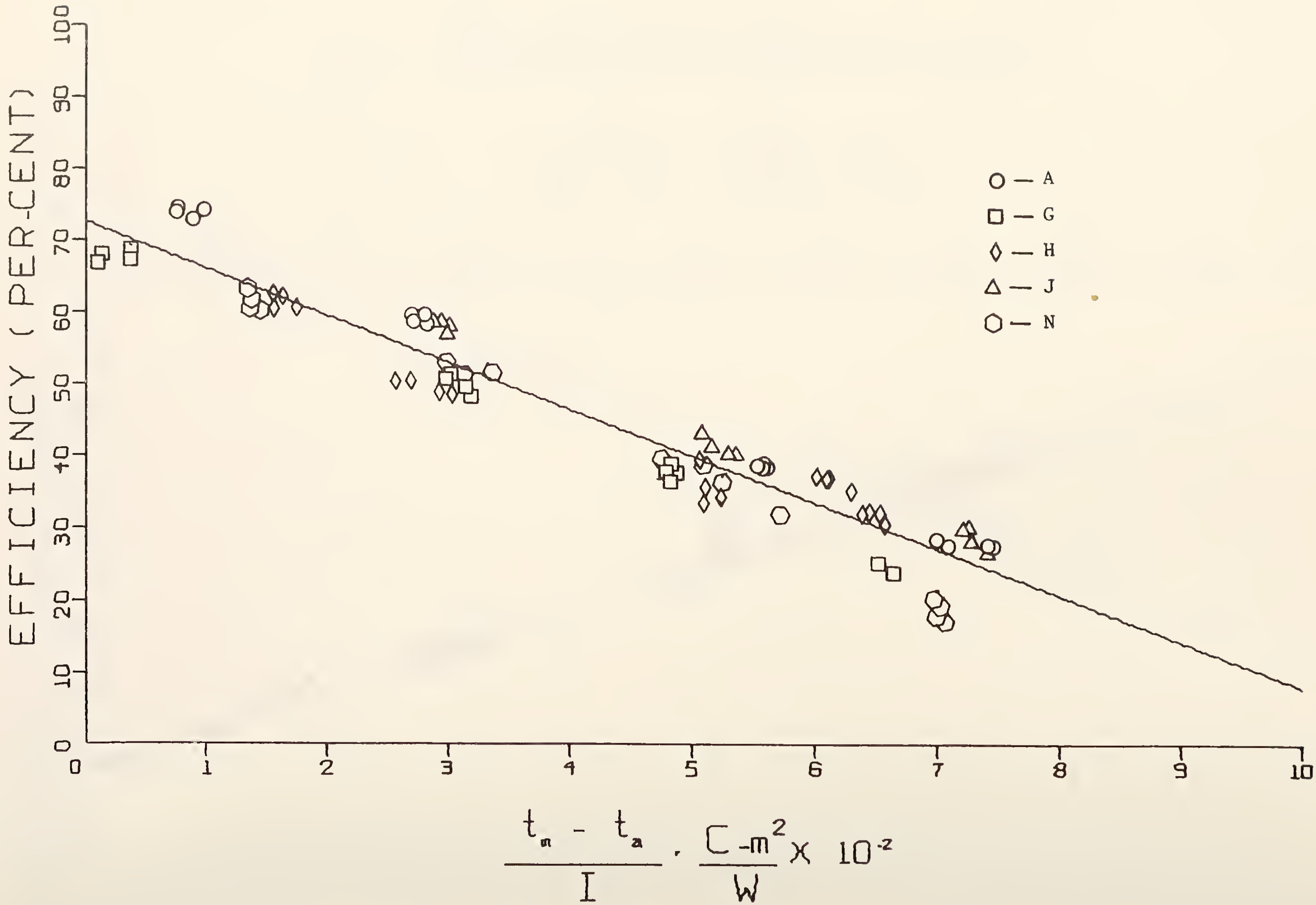


Figure 25 Corrected Results from 5 Facilities for Collector No. 1 Tests Meeting ASHRAE Standard 93-77 Requirements

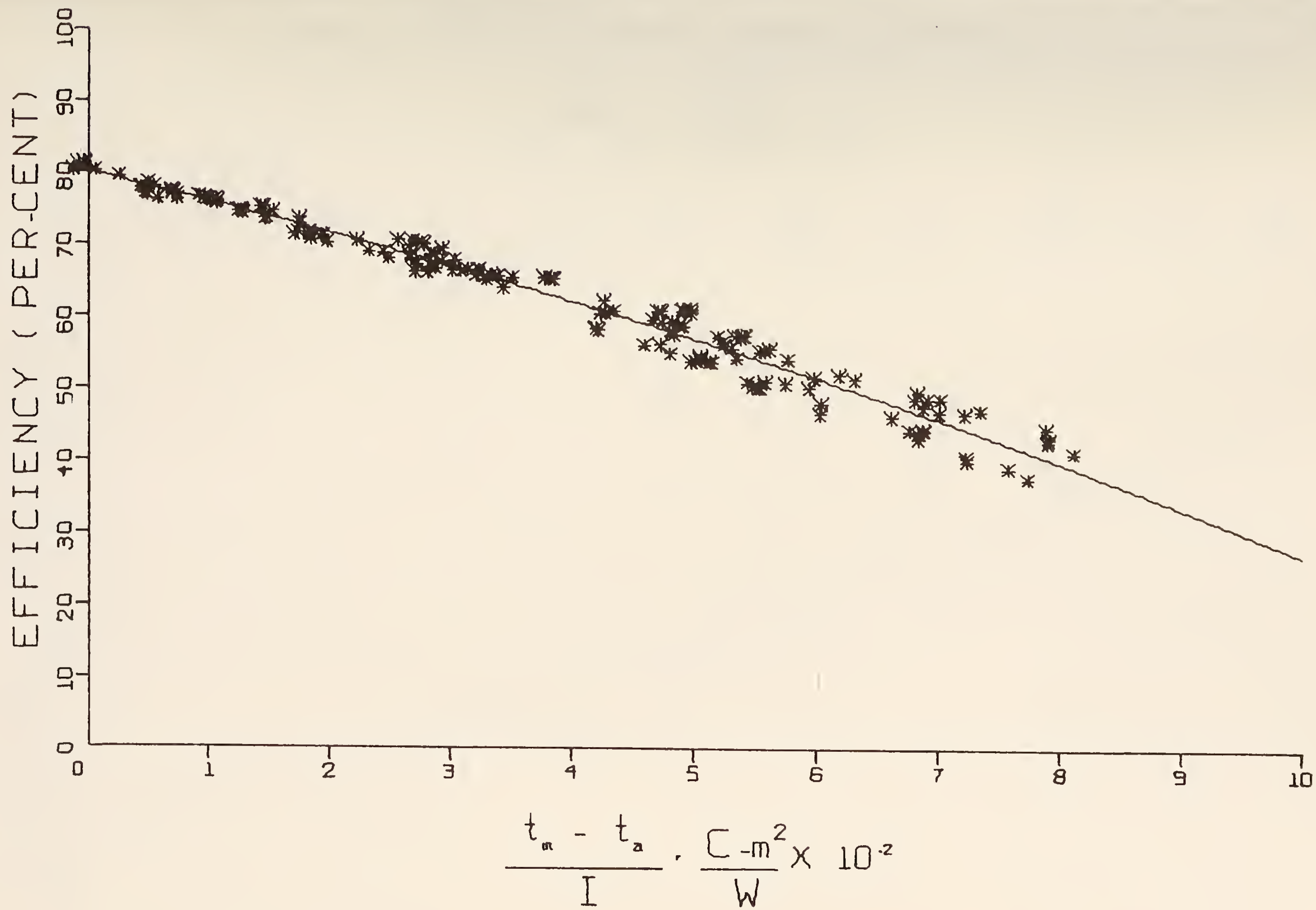


Figure 26 Theoretical Results for Collector No. 2 Based on the Test Conditions Reported by 10 Participants

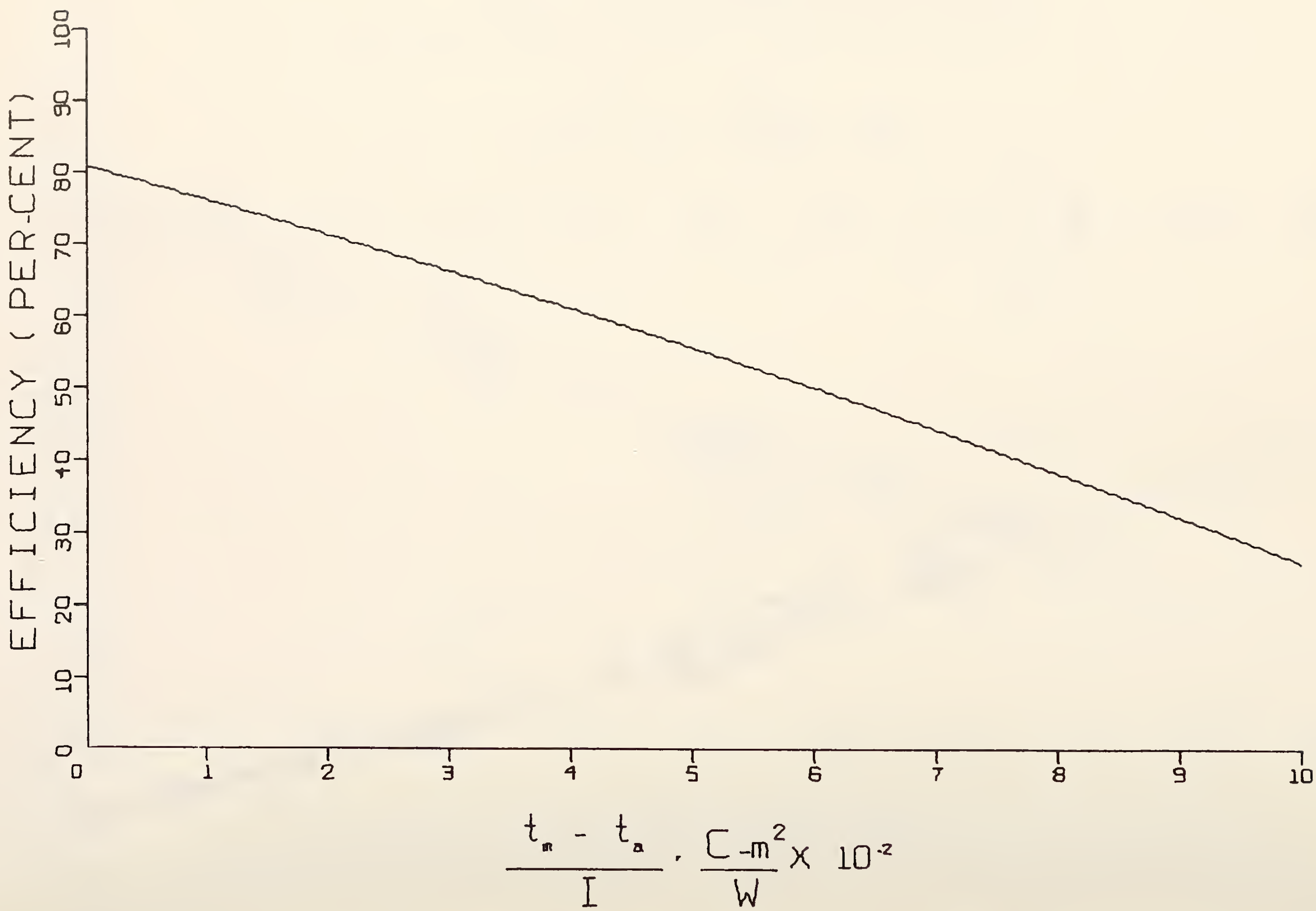


Figure 27 Theoretical Efficiency at "Reference" Conditions for Collector No. 2

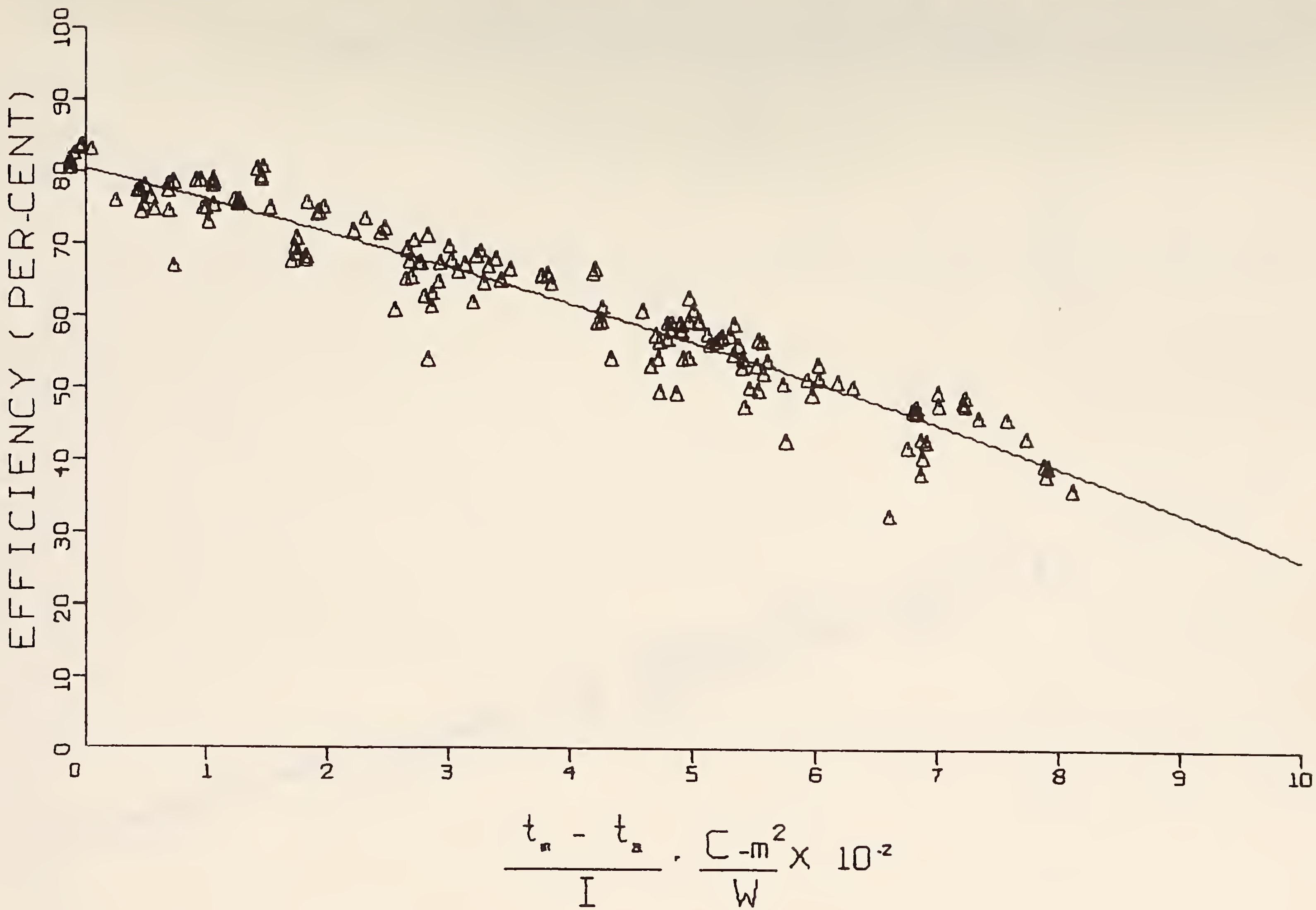


Figure 28 Corrected Results from 10 Facilities for Collector No. 2 Results

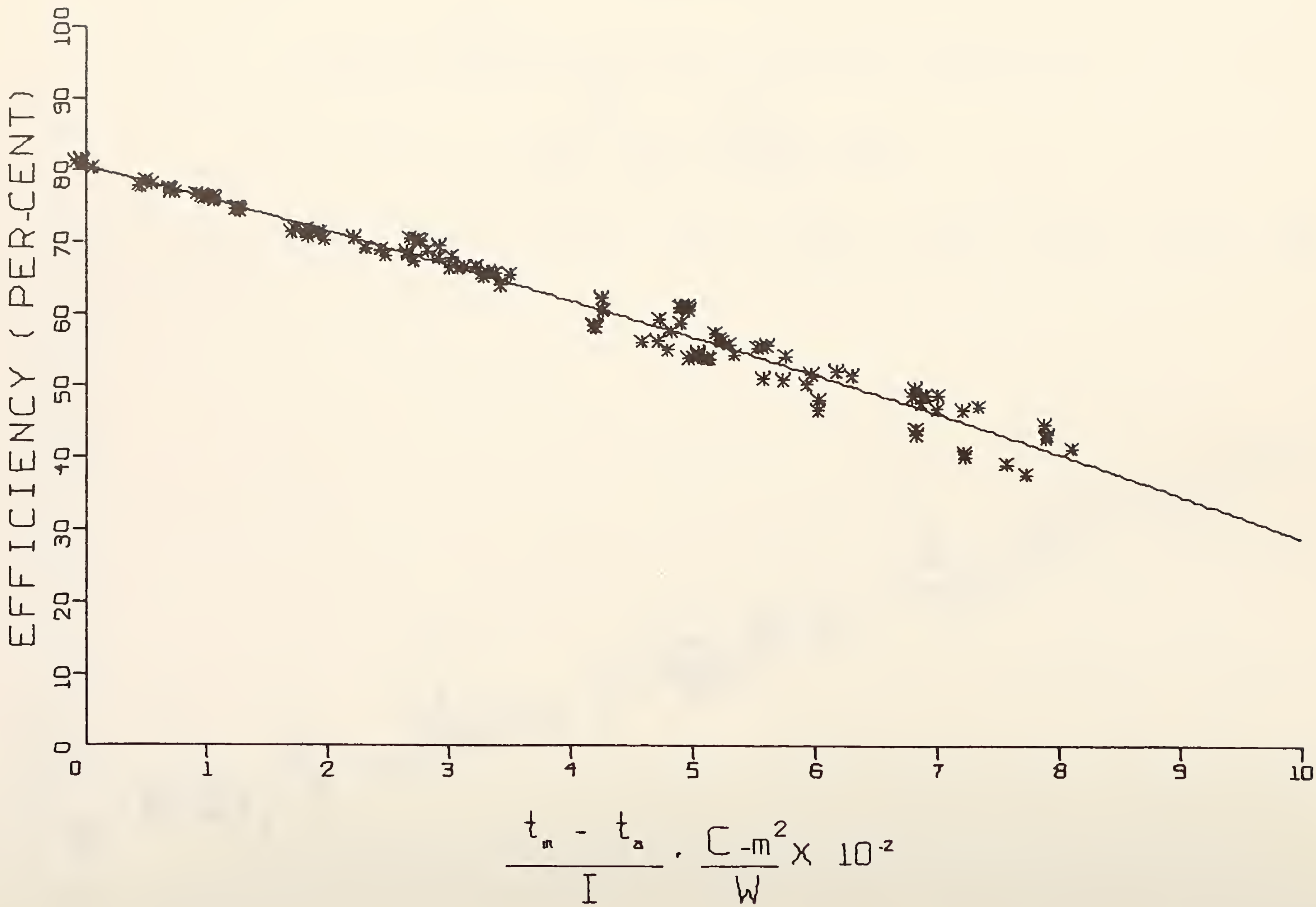


Figure 29 Theoretical Results for Collector No. 2 Based on the Test Conditions Meeting ASHRAE Standard 93-77 Requirements Reported by 7 Participants

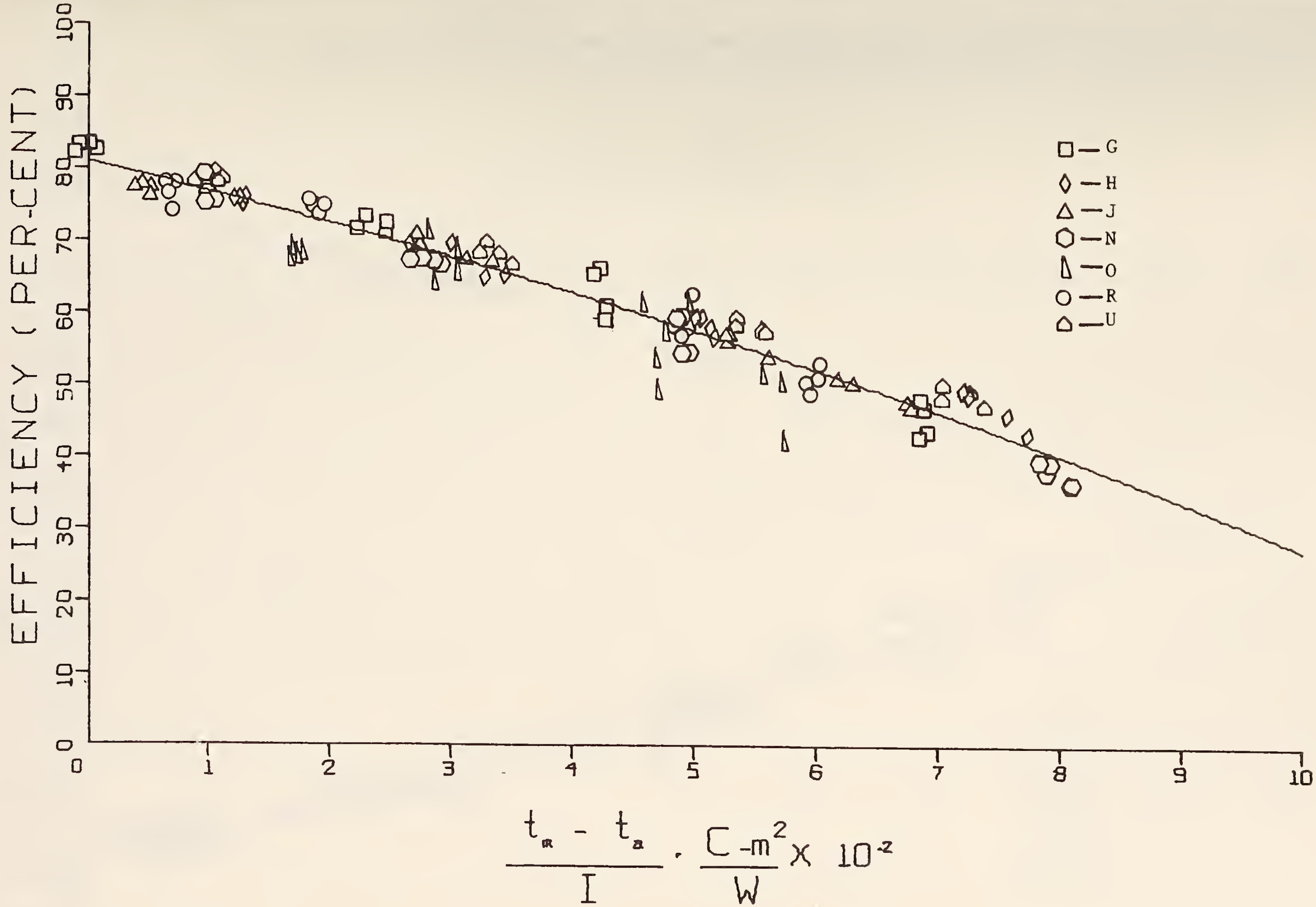


Figure 30 Corrected Results from 7 Facilities for Collector No. 2 Tests Meeting ASHRAE Standard 93-77 Requirements

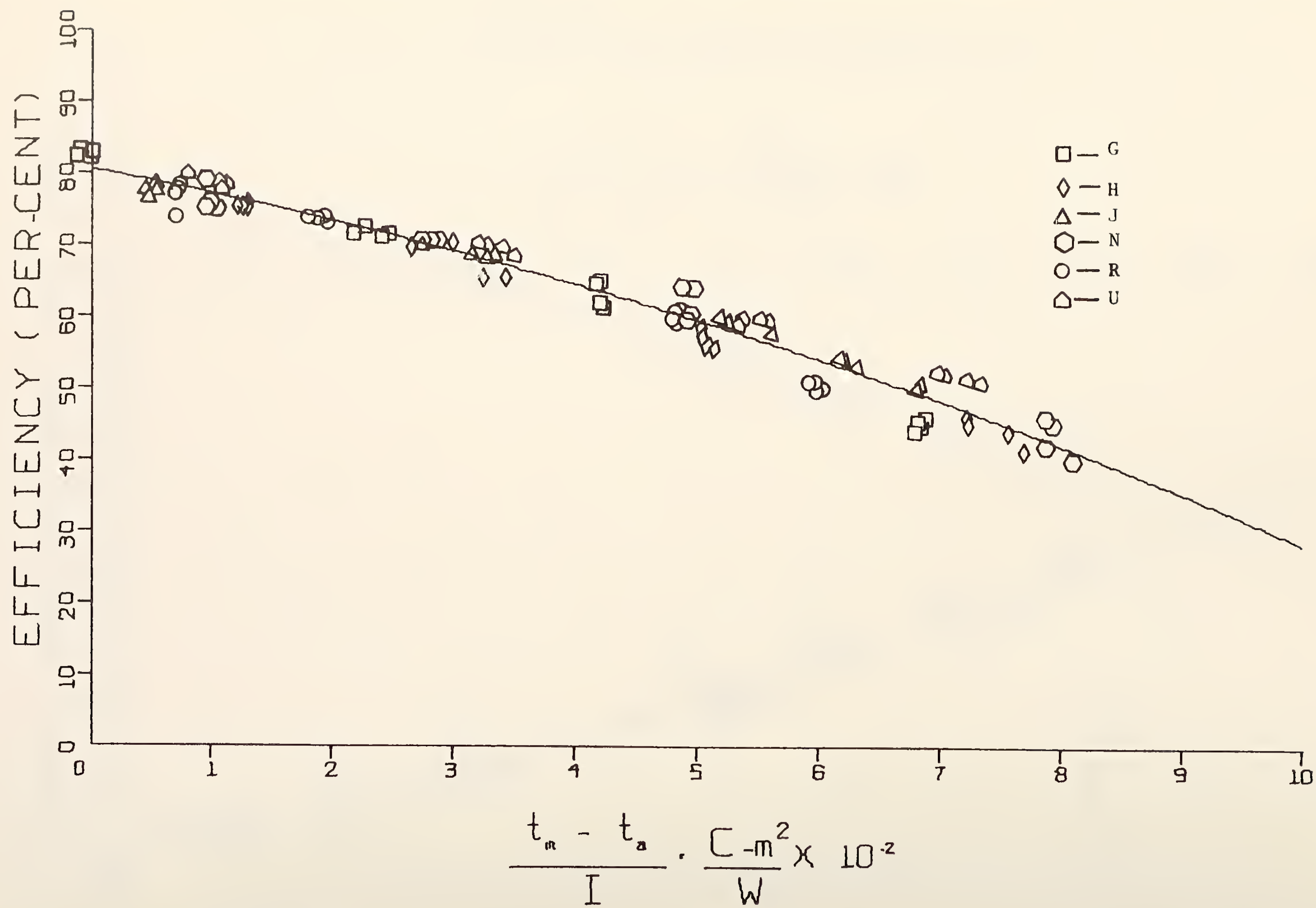


Figure 31 Uncorrected Results from 6 Facilities for Collector No. 2 Tests Meeting ASHRAE Standard 93-77 Requirements

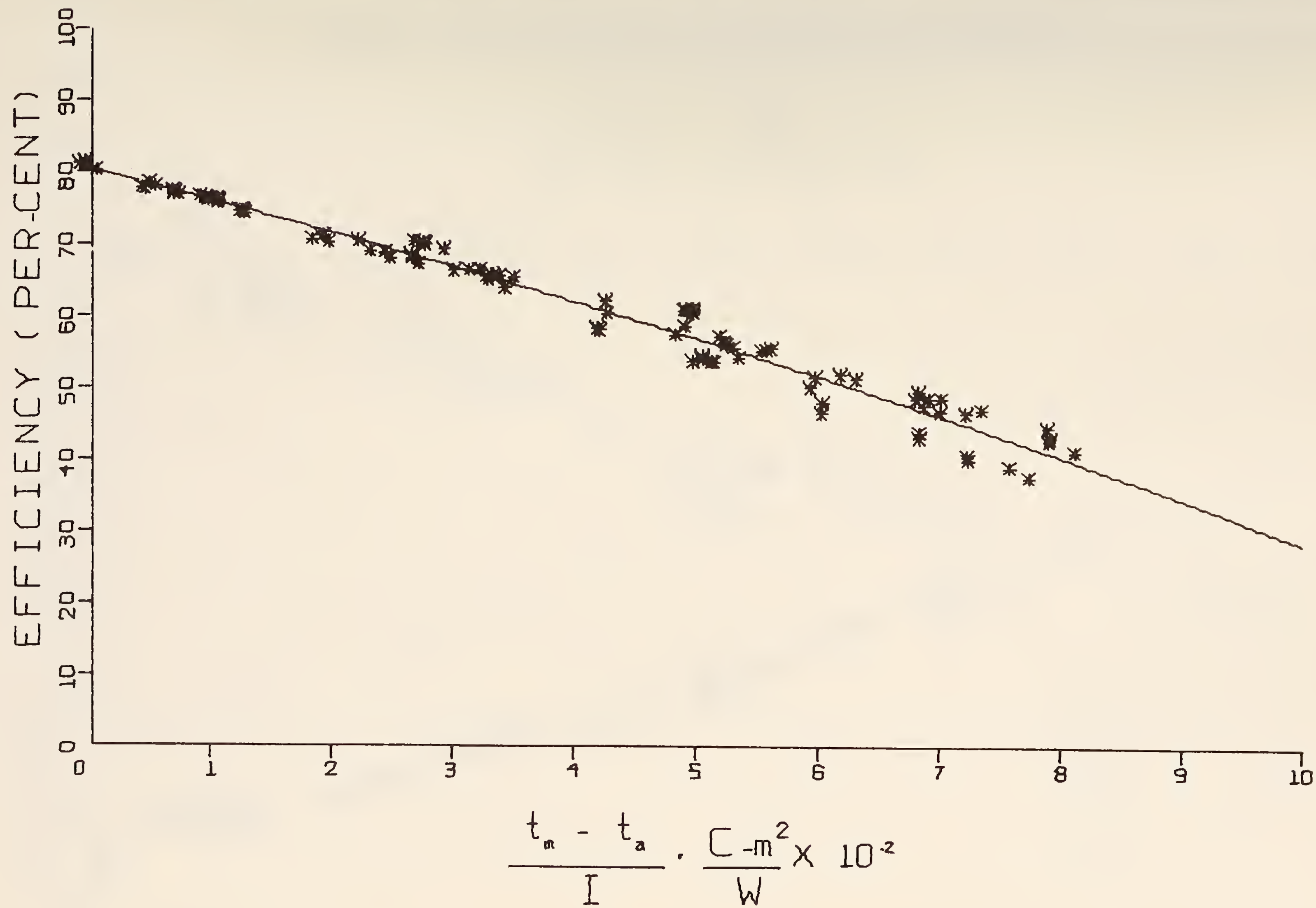


Figure 32 Theoretical Results for Collector No. 2 Based on the Test Conditions Meeting ASHRAE Standard 93-77 Requirements Reported by 6 Participants

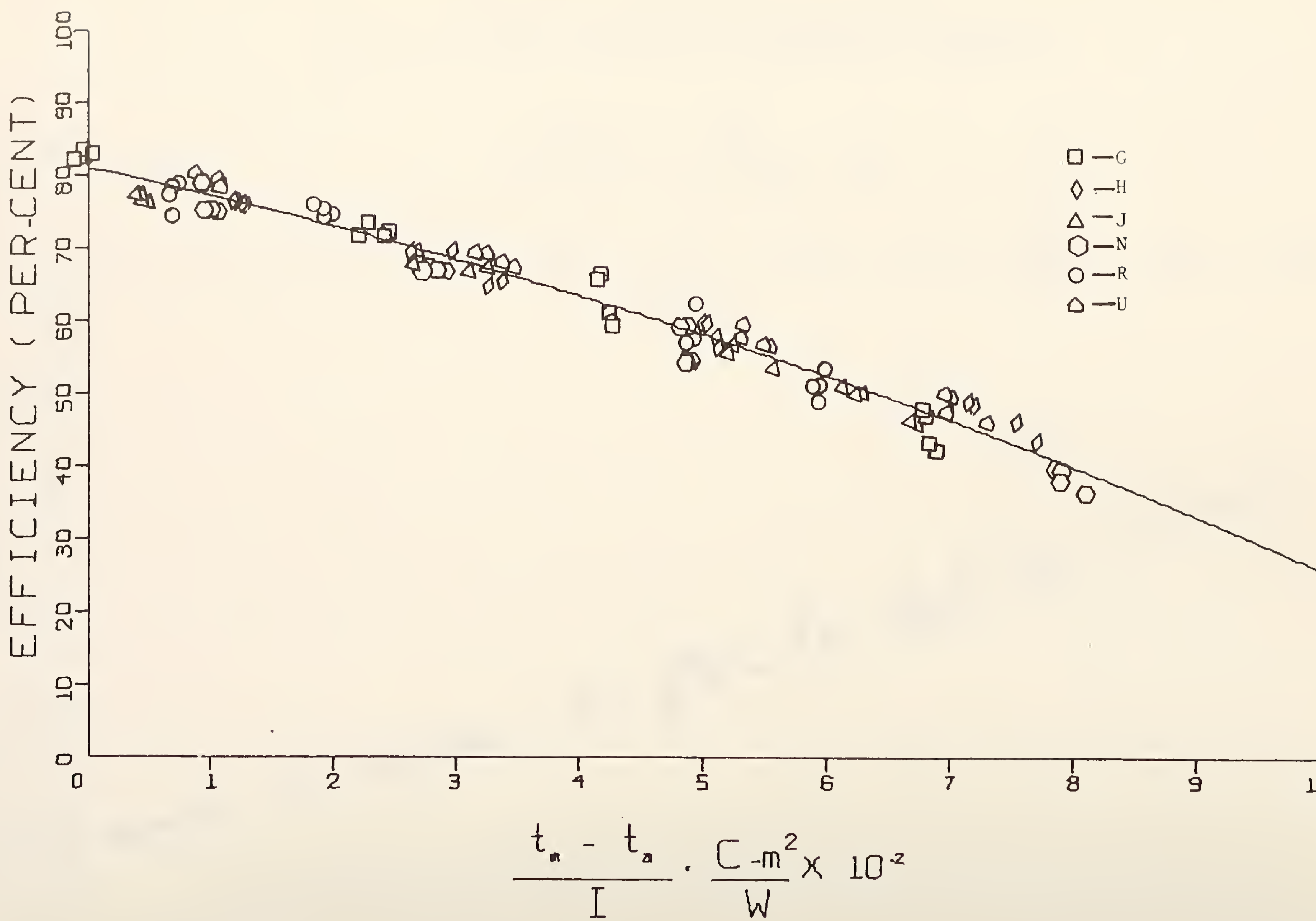


Figure 33 Corrected Results from 6 Facilities for Collector No. 2 Tests Meeting ASHRAE Standard 93-77 Requirements

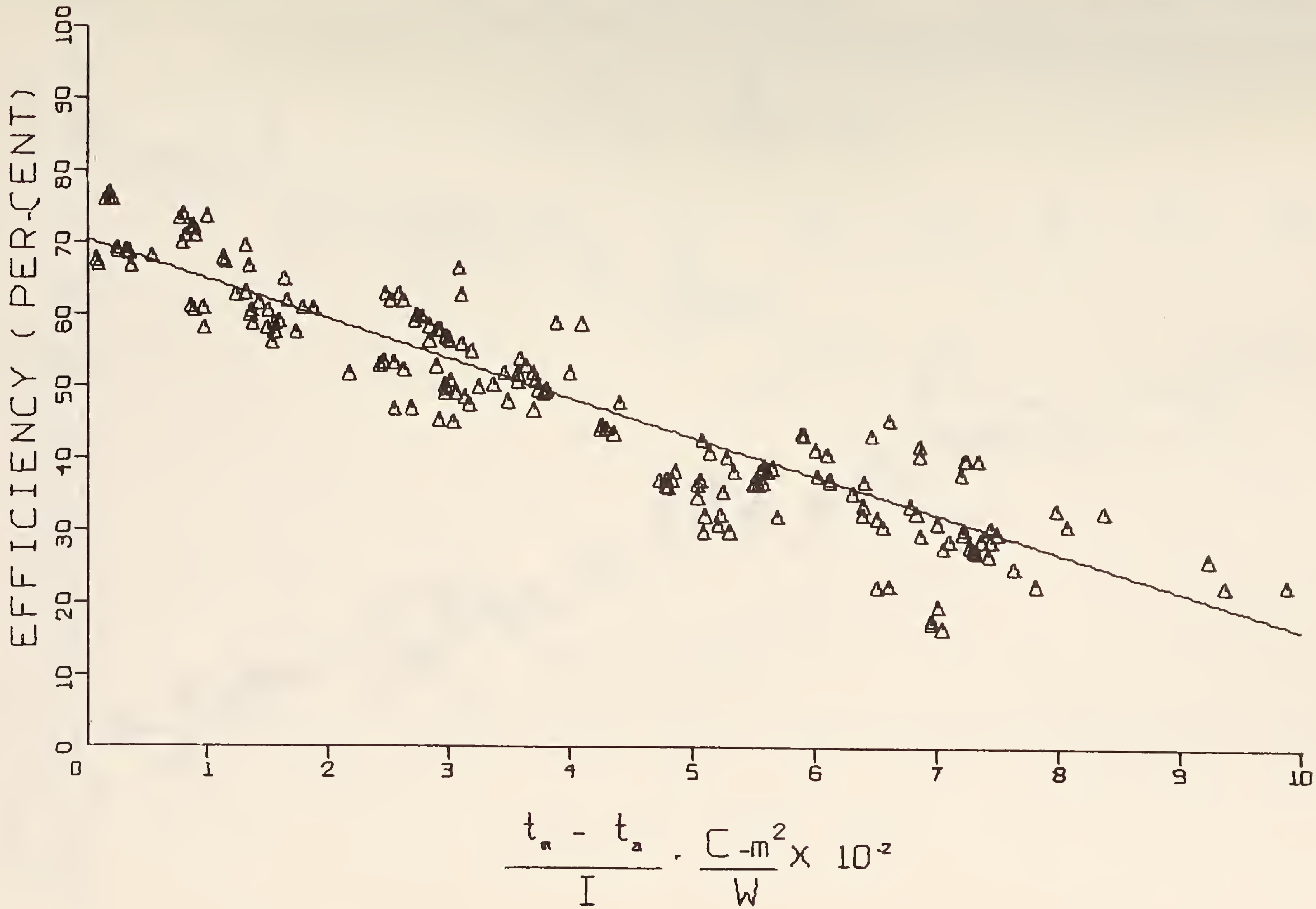


Figure 34 Uncorrected Results from 12 Facilities for Collector No. 1 Tests - Linear Correlation

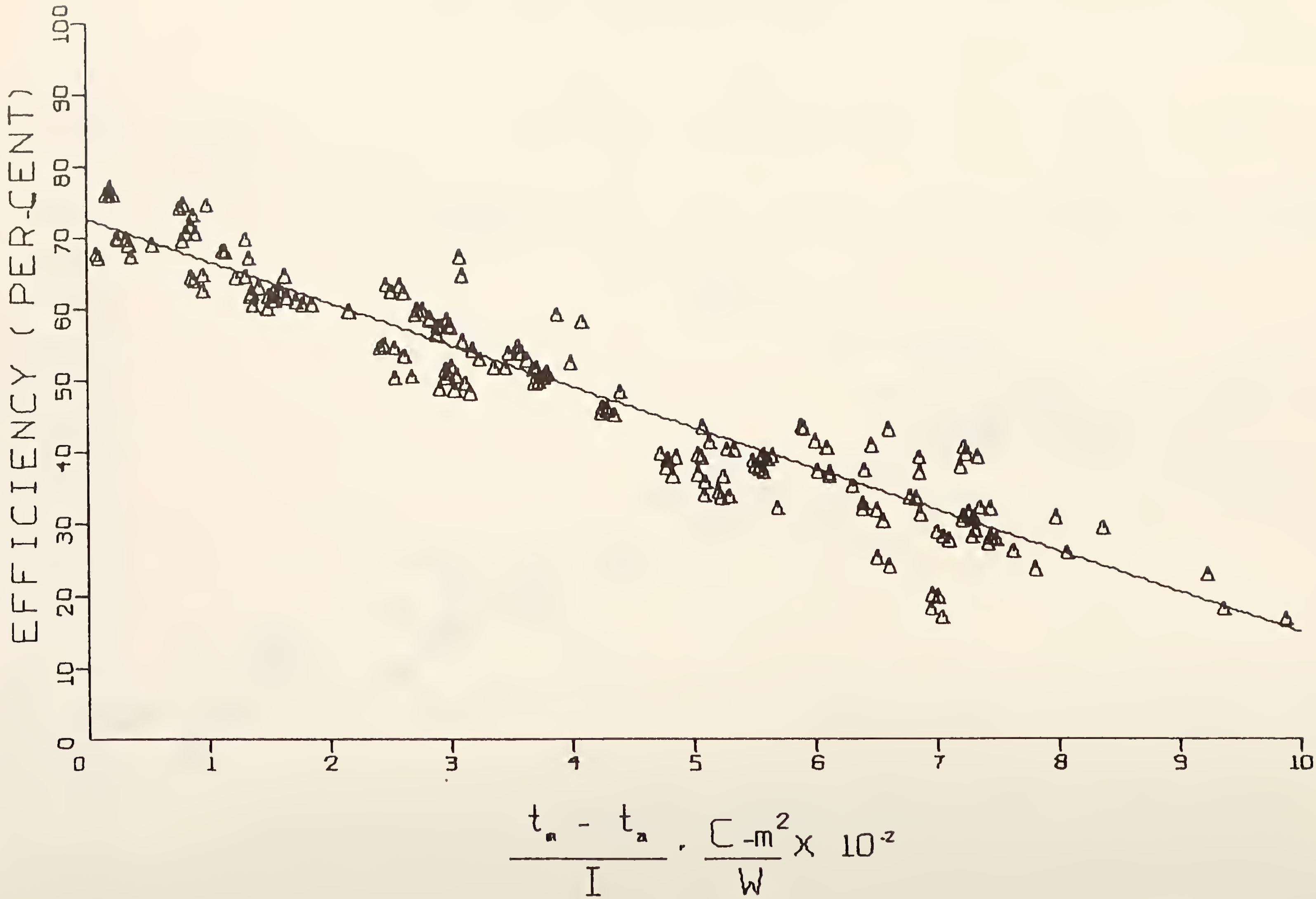


Figure 35 Corrected Results from 12 Facilities for Collector No. 1 Tests - Linear Correlation

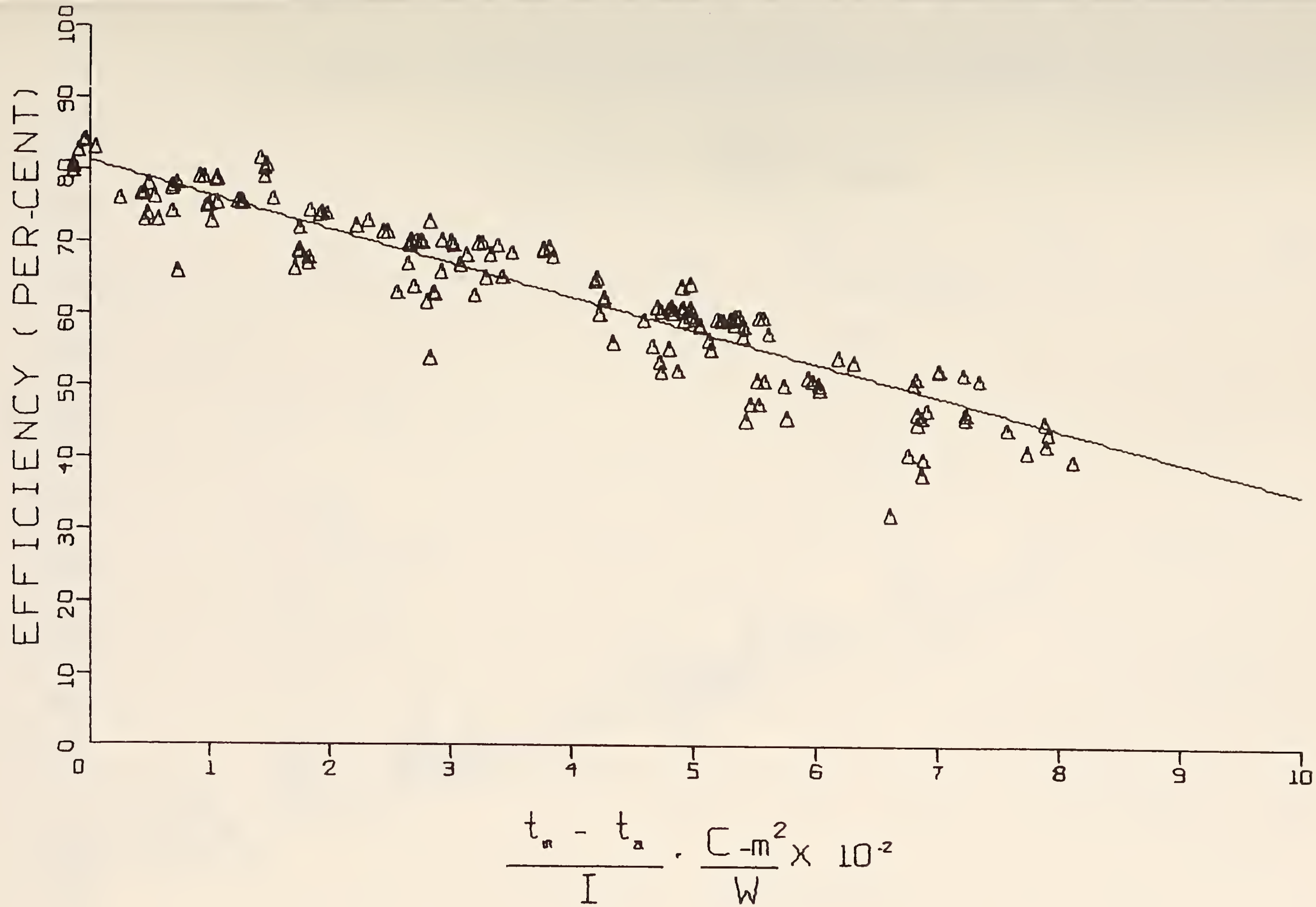


Figure 36 Uncorrected Results from Facilities for Collector No. 2 Tests - Linear Correlation

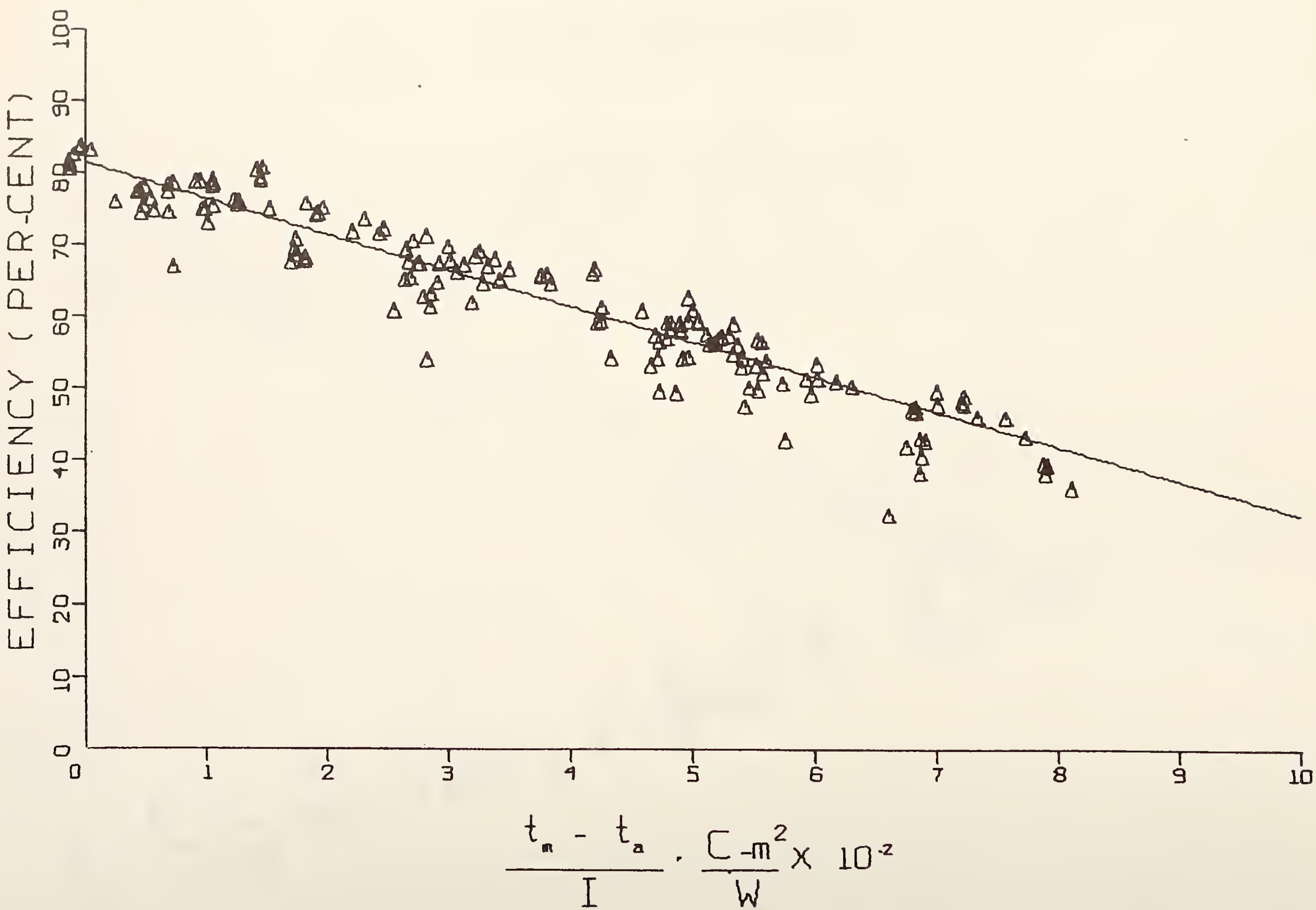


Figure 37 Corrected Results from 10 Facilities for Collector No. 2 Tests - Linear Correlation

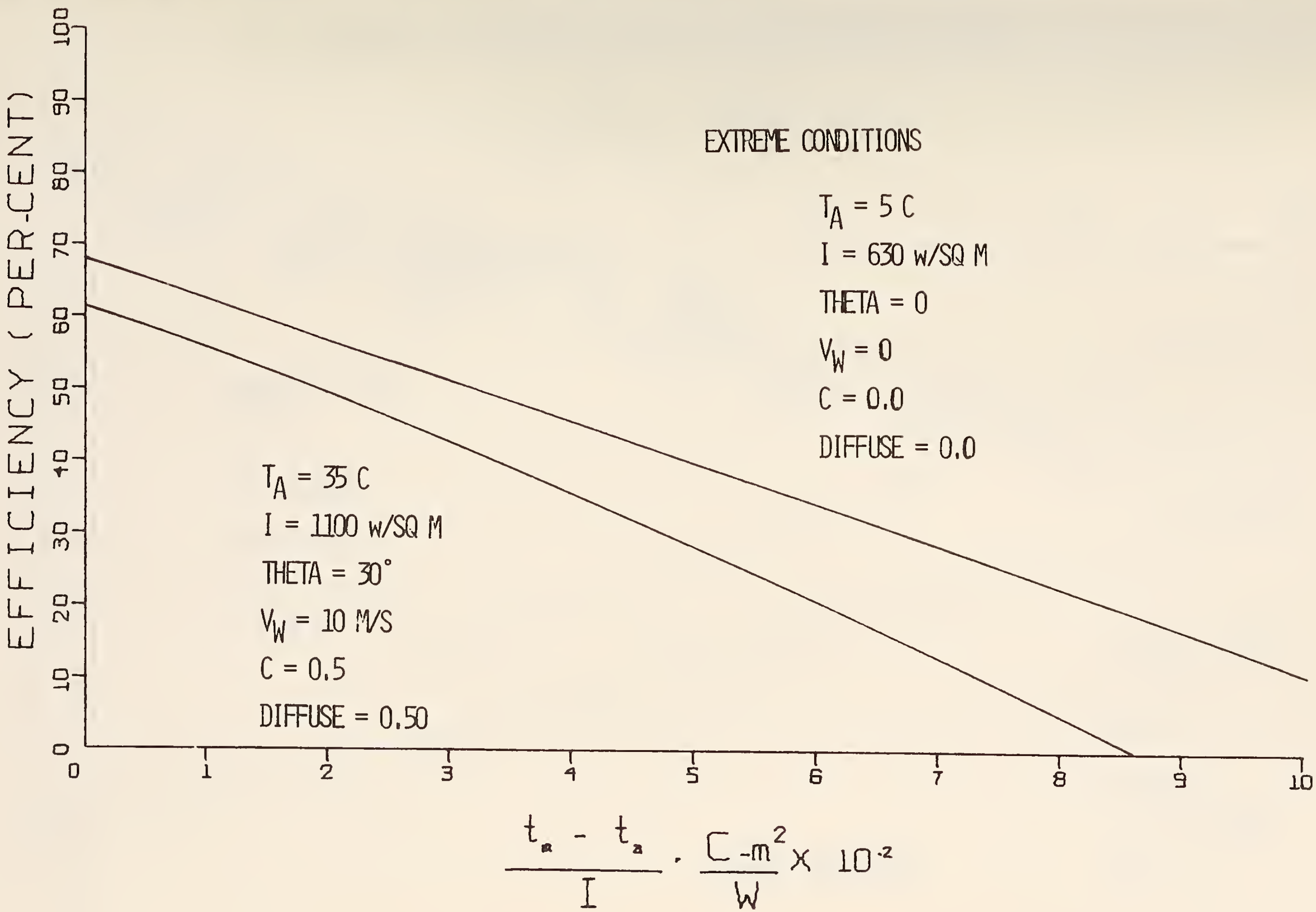


Figure 38 Theoretical Efficiency Curves Under Most and Least Favorable Conditions - Collector No. 1

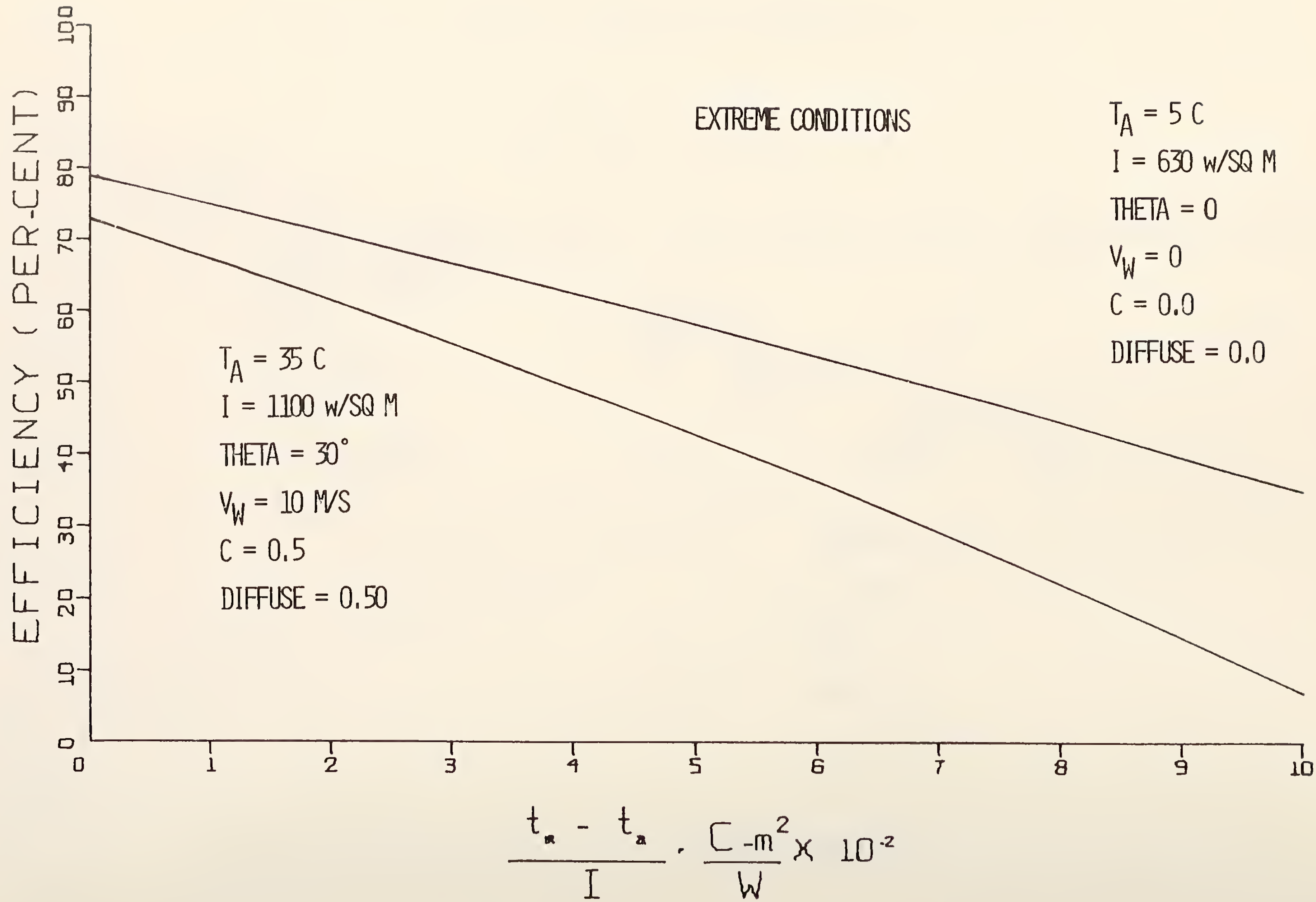


Figure 39 Theoretical Efficiency Curves Under Most and Least Favorable Conditions - Collector No. 2

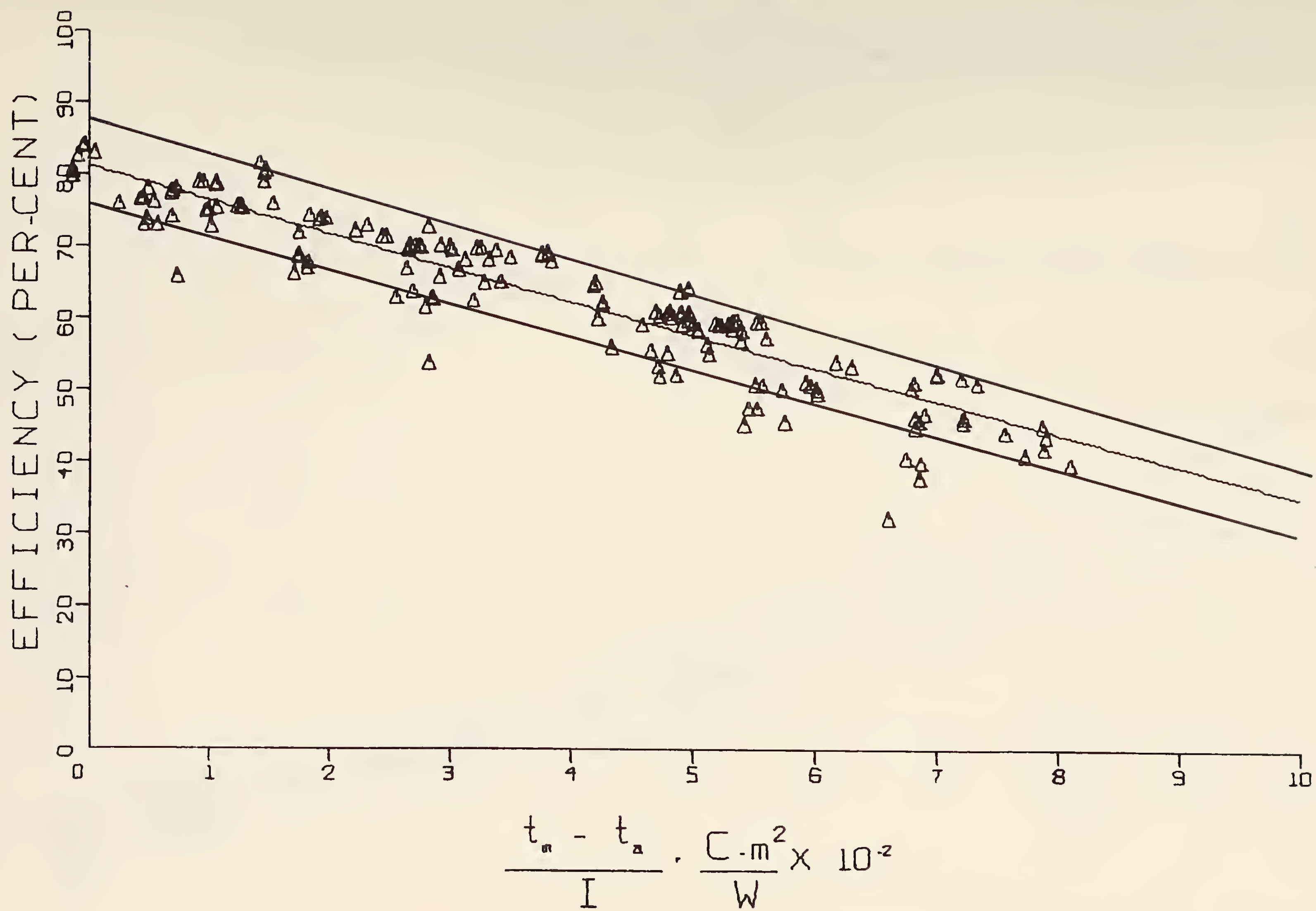


Figure 40 Uncorrected Results from 10 Facilities for Collector No. 2 Tests - Linear Correlation with "Worst Case" Error Band

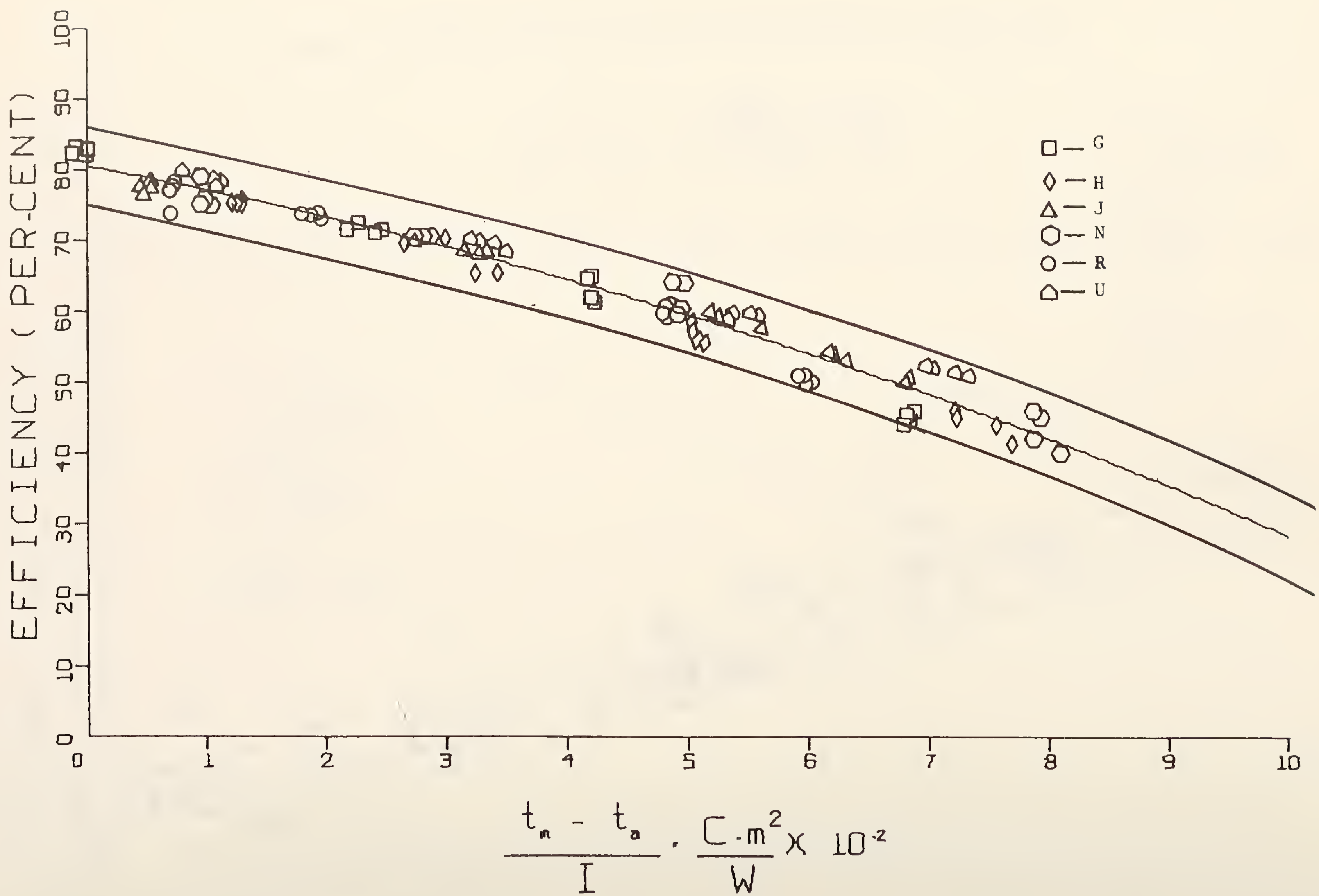


Figure 41 Uncorrected Results from 6 Facilities for Collector No. 2 Tests Meeting ASHRAE Standard 93-77 Requirements with "Worst Case" Error Band

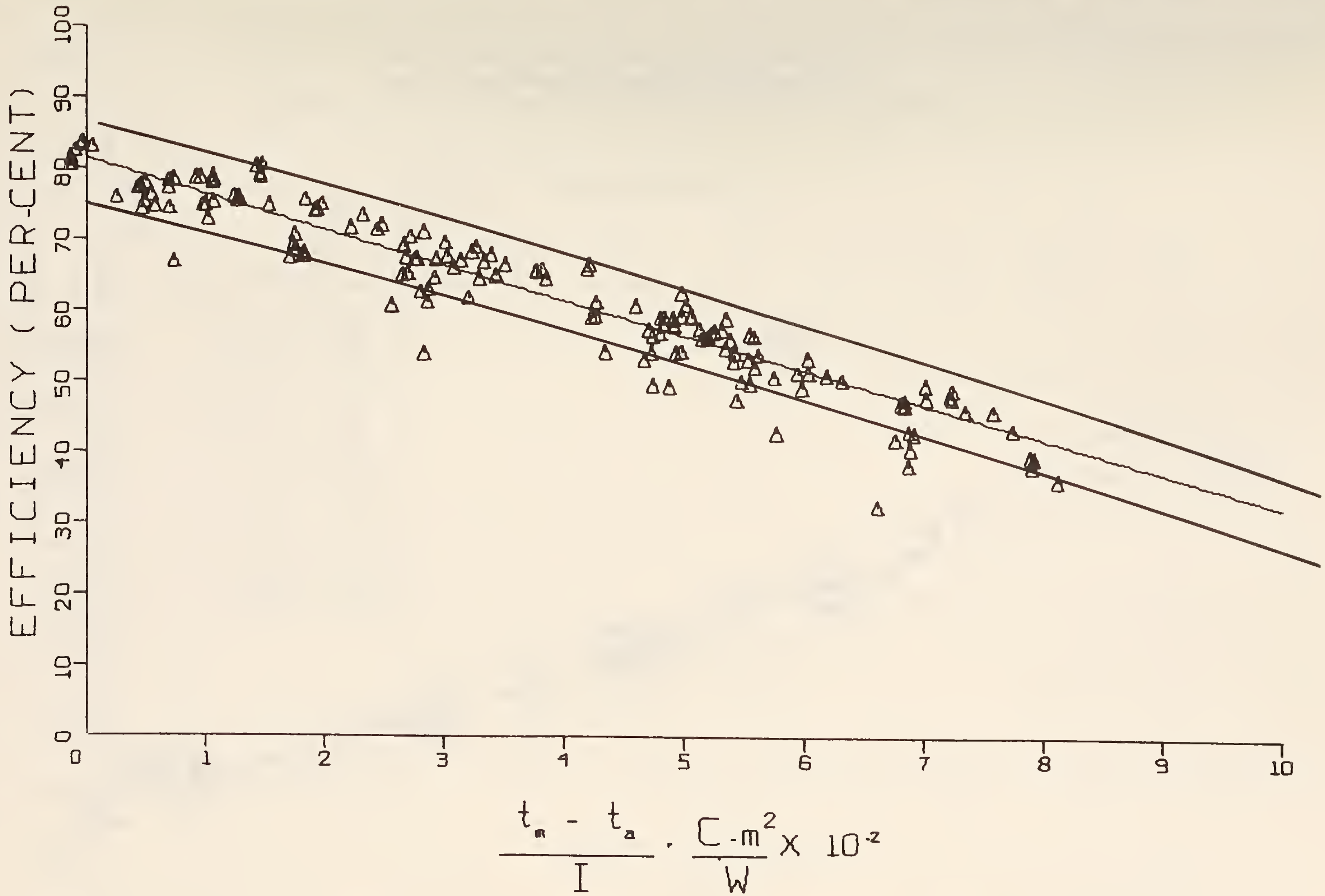


Figure 42 Corrected Results from 10 Facilities for Collector No. 2 Tests - Linear Correlation with "Worst Case" Error Band

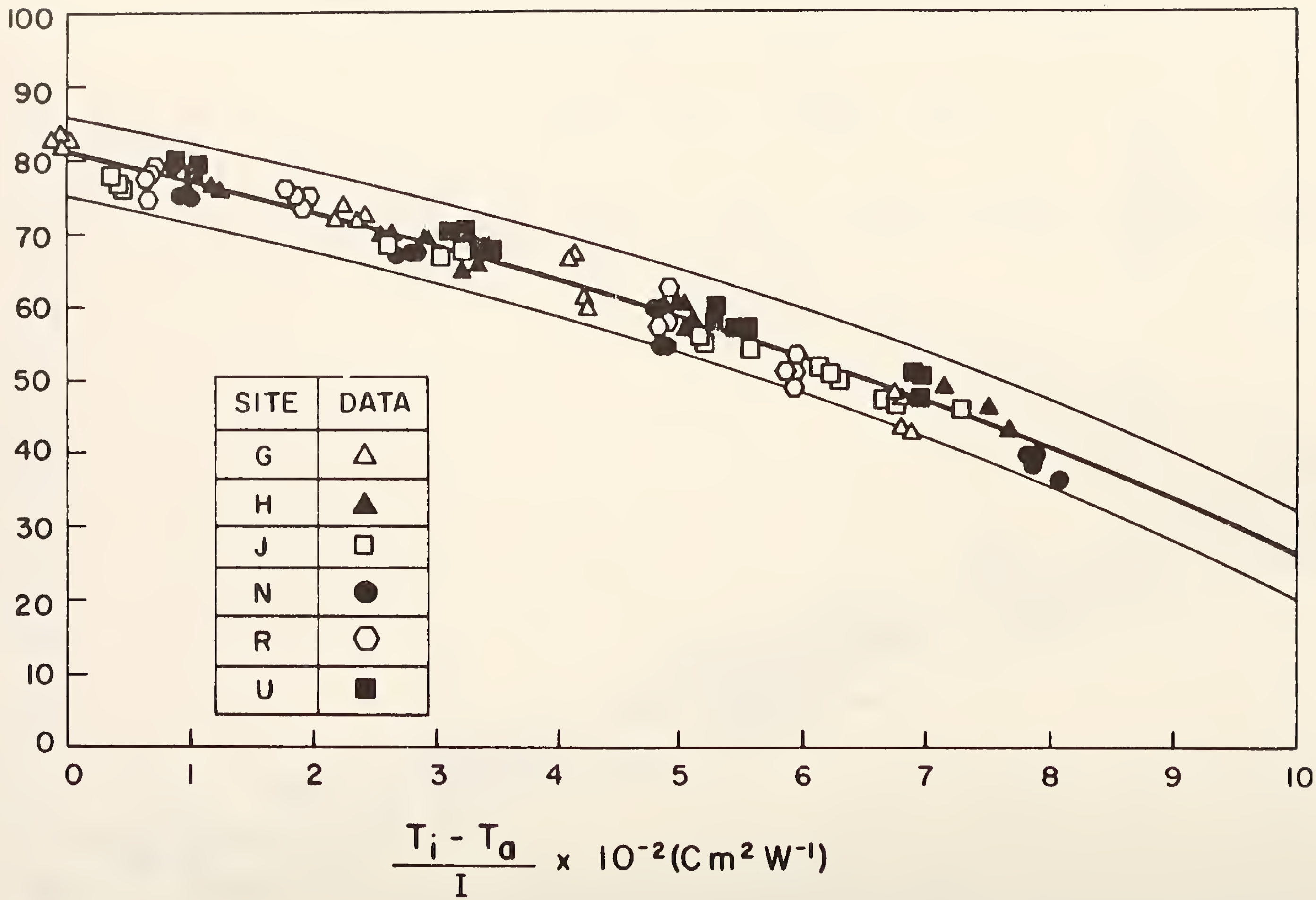


Figure 43 Corrected Results from 6 Facilities for Collector No. 2 Tests Meeting ASHRAE Standard 93-77 Requirements with "Worst Case" Error Band

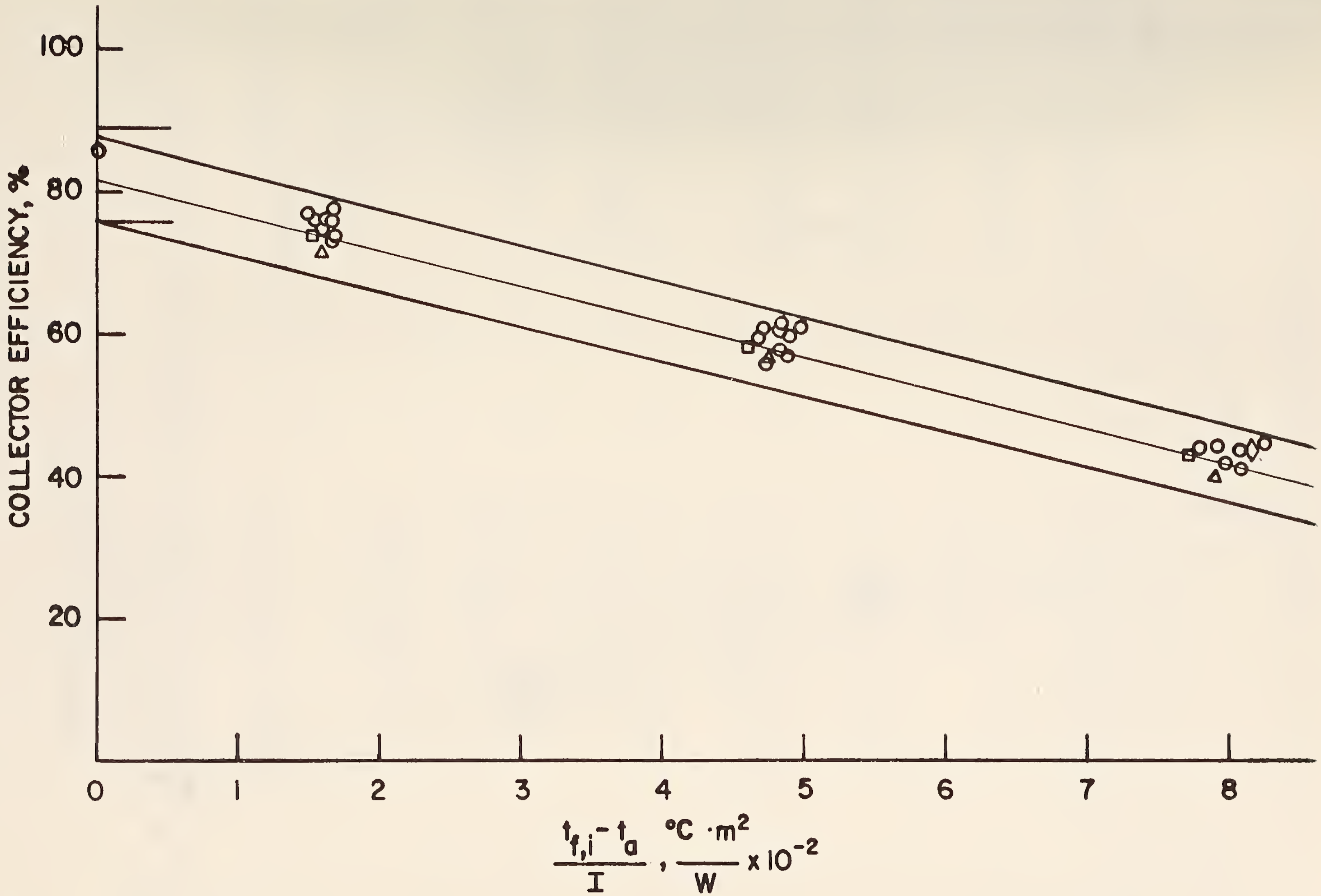


Figure 44 Expected Data Scatter for Collector No. 2 from 10 Hypothetical Test Facilities which Meet the Requirements of ASHRAE Standard 93-77, I = 630 W/m^2

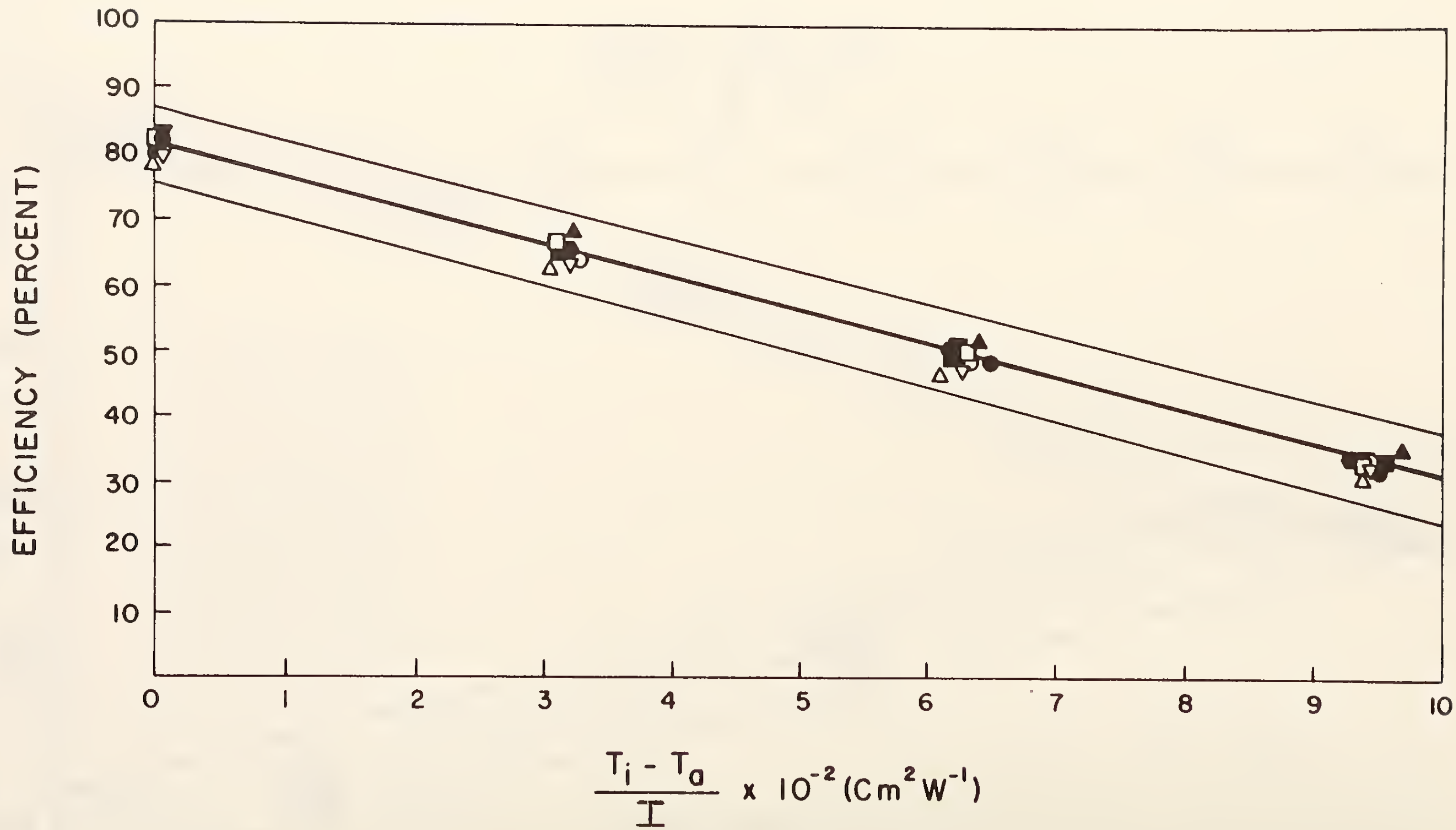


Figure 45 Expected Data Scatter for Collector No. 2 from 10 Hypothetical Test Facilities which Meet the Requirements of ASHRAE Standard 93-77, $I = 1000\ W/m^2$

Appendix A

List of Round Robin Participants

Organization	Collector #1	Collector #2	Organization	Collector #1	Collector #2
Arthur D. Little, Inc., Cambridge, Massachusetts W. David Lee	X	X	PPG Industries Pittsburgh, Pennsylvania M. Barker		X
Arizona State University Tempe, Arizona B.D. Wood	X	X	University of Dayton Dayton, Ohio H.E. Smith	X	X
Chamberlain Manufacturing Co. Waterloo, Iowa J.D. Morris	X		University of Florida Gainsville, Florida E.A. Farber	X	X
Desert Sunshine Exposure Tests, Inc. Phoenix, Arizona G. Zerlaut	X	X	University of Tennessee at Chattanooga Chattanooga, Tennessee L. Russell	X	X
Honeywell, Inc. Minneapolis, Minnesota J.D. Kopecki	X	X	University of Texas at Arlington Arlington, Texas T.J. Lawley	X	X
Lennox Industries, Inc. Marshalltown, Iowa David C. Lee	X	X	University of Utah Salt Lake City, Utah R.E. Boehm	X	X
Lockheed Palo Alto Research Lab Palo Alto, California K.L. Marshall	X	X	University of Tulsa Tulsa, Oklahoma B.V. Ketchum	X	X
Martin Marietta Corporation Denver, Colorado J. Kidd	X	X	University of Miami Coral Gables, Florida L.E. Poteat	X	
New Mexico State University Las Cruces, New Mexico H.L. Connell	X	X	University of Califor- nia at Los Angeles Los Angeles, California H. Buchberg	X	X

Organization	Collector #1	Collector #2
Virginia Polytechnic Institute and State University Blacksburg, Virginia W.C. Thomas	X	X
Civil Engineering Laboratory/NCBC Port Hueneme, California E. Durlac		X
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio F. Simon	X	
University of California Los Alamos Scientific Laboratory Los Alamos, New Mexico S.W. Moore	X	X
National Bureau of Standards Washington, D.C. J. Jenkins	X	X

Appendix B

Data Used in Analyzing the Effect of Environmental Conditions

Data, measured results, and the theoretical analysis for each test facility are given in the following tabulations. "XPARM" is the abscissa of the collector efficiency curve as reported in terms of mean fluid temperature. The theoretically determined parameters are shown below the measured values. "PARM" entrees are the corresponding abscissa values of the collector efficiency curve in terms of the inlet fluid temperature.

COLLECTOR TEST FACILITY,A PPG

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	10.2	45.0	18.0	26.6	0.0396	2.4	11.5	962.	0.0131	72.3	0.50
2	9.6	45.0	19.4	27.0	0.0396	1.7	10.2	978.	0.0120	73.4	0.50
3	11.8	45.0	19.6	27.5	0.0396	1.8	9.1	981.	0.0123	74.0	0.50
4	17.4	45.0	20.2	29.7	0.0396	2.0	9.5	953.	0.0142	73.7	0.50
5	7.6	45.0	8.1	36.2	0.0396	6.1	5.6	1032.	0.0306	59.2	0.50
6	13.5	45.0	8.8	36.3	0.0396	5.2	4.4	1003.	0.0308	60.0	0.50
7	17.0	45.0	8.9	36.3	0.0396	5.4	6.3	984.	0.0313	59.8	0.50
8	20.7	45.0	9.1	36.3	0.0396	5.5	7.4	959.	0.0318	58.5	0.50
9	10.5	45.0	15.4	68.9	0.0396	4.3	14.2	953.	0.0583	38.4	0.50
10	9.1	45.0	15.1	68.8	0.0396	4.5	13.7	950.	0.0587	38.9	0.50
11	9.4	45.0	15.7	68.9	0.0396	3.8	13.6	956.	0.0577	38.6	0.50
12	11.2	45.0	15.9	68.9	0.0396	4.0	12.8	950.	0.0580	39.1	0.50
13	10.9	45.0	11.2	83.1	0.0396	2.9	7.4	1013.	0.0727	28.8	0.50
14	10.2	45.0	12.3	82.9	0.0396	1.1	7.8	1009.	0.0718	31.3	0.50
15	18.0	45.0	13.1	83.5	0.0396	1.4	9.0	946.	0.0761	30.6	0.50
16	21.4	45.0	14.1	83.1	0.0396	1.7	8.9	921.	0.0767	29.9	0.50

RUN	TSKY (C)	HW "(W/SQM-C)"	UL "(W/SQM-C)"	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	1.1	14.8	5.97	0.91	72.3	64.3	65.2	73.2	0.0089
2	3.1	12.2	5.99	0.91	73.4	65.0	65.8	74.2	0.0078
3	3.3	12.5	5.99	0.91	74.0	64.9	65.7	74.7	0.0081
4	4.2	13.3	6.01	0.90	73.7	63.8	64.6	74.6	0.0100
5	-12.8	28.9	5.92	0.91	59.2	55.2	55.2	59.2	0.0272
6	-11.8	25.5	5.91	0.91	60.0	55.2	55.1	59.9	0.0274
7	-11.7	26.2	5.92	0.91	59.8	54.8	54.8	59.9	0.0278
8	-11.4	26.6	5.92	0.91	58.5	54.3	54.6	58.7	0.0284
9	-2.6	22.0	6.27	0.90	38.4	37.3	37.9	39.0	0.0561
10	-3.0	22.8	6.27	0.90	38.9	37.1	37.7	39.5	0.0565
11	-2.2	20.1	6.25	0.90	38.6	37.8	38.2	39.1	0.0556
12	-1.9	20.9	6.26	0.90	39.1	37.7	38.2	39.6	0.0558
13	-8.5	16.7	6.32	0.90	28.8	29.4	28.3	27.7	0.0710
14	-6.9	9.9	6.13	0.91	31.3	31.4	28.9	28.8	0.0700
15	-5.8	11.0	6.18	0.90	30.6	28.4	26.0	28.1	0.0744
16	-4.4	12.2	6.22	0.90	29.9	27.8	25.6	27.8	0.0749

COLLECTOR TEST FACILITY,E PPG

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	22.7	45.0	13.9	27.5	0.0192	0.9	13.8	950.	0.0207	61.7	0.00
2	19.6	45.0	14.5	29.0	0.0192	1.1	14.3	963.	0.0214	60.6	0.00
3	19.6	45.0	15.3	28.0	0.0192	0.9	15.2	959.	0.0198	63.1	0.00
4	21.0	45.0	15.6	27.4	0.0193	1.5	15.2	951.	0.0189	62.8	0.00
5	22.7	45.0	13.2	38.3	0.0194	1.3	16.5	953.	0.0318	52.4	0.00
6	21.3	45.0	13.6	38.1	0.0193	1.5	16.7	962.	0.0311	53.4	0.00
7	21.7	45.0	13.8	37.4	0.0192	3.2	16.3	959.	0.0302	53.5	0.00
8	22.9	45.0	14.4	37.3	0.0192	3.3	14.5	944.	0.0299	53.1	0.00
9	24.2	45.0	21.1	68.0	0.0183	2.1	17.5	896.	0.0559	32.4	0.00
10	22.3	45.0	22.2	68.5	0.0184	3.6	17.5	918.	0.0542	34.9	0.00
11	23.0	45.0	23.9	68.8	0.0186	4.0	22.1	936.	0.0519	36.3	0.00
12	25.5	45.0	24.0	68.5	0.0188	5.4	32.8	839.	0.0563	30.1	0.00
13	23.0	45.0	19.3	81.0	0.0176	2.5	36.0	809.	0.0791	25.0	0.00
14	22.3	45.0	20.0	81.4	0.0175	2.1	39.2	786.	0.0808	22.7	0.00
15	22.7	45.0	21.2	82.1	0.0178	2.4	30.5	886.	0.0721	29.6	0.00
16	23.5	45.0	20.0	80.9	0.0179	3.4	31.6	832.	0.0762	27.3	0.00

RUN	TSKY (C)	HW "(W/SQM-C)"	UL	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	-4.7	9.1	5.87	0.90	61.7	60.9	62.3	63.1	0.0143
2	-3.9	9.9	5.86	0.90	60.6	60.6	61.9	61.9	0.0151
3	-2.7	9.1	5.87	0.90	63.1	61.4	62.9	64.6	0.0132
4	-2.3	11.4	5.90	0.90	62.8	61.7	63.3	64.4	0.0124
5	-5.7	10.6	5.86	0.90	52.4	54.6	55.7	53.4	0.0263
6	-5.1	11.4	5.88	0.90	53.4	55.0	56.2	54.6	0.0255
7	-4.8	17.9	5.95	0.90	53.5	55.1	56.7	55.0	0.0246
8	-4.0	18.2	5.96	0.90	53.1	55.4	56.9	54.6	0.0243
9	5.5	13.7	6.20	0.90	32.4	39.2	40.3	33.6	0.0523
10	7.0	19.4	6.32	0.89	34.9	39.5	41.5	36.9	0.0504
11	9.5	20.9	6.37	0.89	36.3	40.3	43.0	39.0	0.0480
12	9.6	26.2	6.41	0.89	30.1	36.2	39.9	33.8	0.0530
13	2.9	15.2	6.32	0.89	25.0	23.5	24.7	26.2	0.0763
14	3.9	13.7	6.29	0.89	22.7	22.5	23.4	23.7	0.0781
15	5.6	14.8	6.36	0.89	29.6	28.0	29.8	31.3	0.0687
16	3.9	18.6	6.39	0.89	27.3	25.0	26.8	29.1	0.0732

COLLECTOR TEST FACILITY,F PPG

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	34.0	30.0	15.3	46.1	0.0324	7.2	11.4	828.	0.0402	51.0	0.00
2	25.0	30.0	15.3	48.3	0.0330	7.6	11.1	882.	0.0403	49.6	0.00
3	23.0	30.0	15.6	50.6	0.0311	8.5	10.9	876.	0.0432	52.1	0.00
4	28.0	30.0	15.6	51.9	0.0310	8.0	11.5	823.	0.0472	48.0	0.00
5	28.0	30.0	14.7	26.4	0.0296	6.3	10.9	865.	0.0178	66.8	0.00
6	18.5	30.0	17.8	30.3	0.0303	6.3	10.7	945.	0.0176	69.6	0.00
7	18.0	30.0	21.7	32.5	0.0298	6.3	10.8	953.	0.0157	67.9	0.00
8	23.0	30.0	22.8	33.3	0.0300	6.3	12.3	910.	0.0159	67.5	0.00
9	19.0	30.0	17.8	75.3	0.0347	3.6	11.8	943.	0.0632	40.8	0.00
10	15.0	30.0	18.6	75.6	0.0348	3.6	11.8	964.	0.0614	43.5	0.00
11	15.0	30.0	19.7	76.4	0.0348	3.6	12.0	963.	0.0612	43.6	0.00
12	19.0	30.0	20.6	76.7	0.0350	3.6	12.4	935.	0.0622	41.5	0.00
13	16.0	30.0	24.4	94.2	0.0299	7.2	19.6	948.	0.0754	28.9	0.00
14	10.0	30.0	24.7	94.4	0.0301	7.2	19.1	955.	0.0747	27.4	0.00
15	10.0	30.0	25.3	94.7	0.0301	7.6	18.7	955.	0.0744	28.1	0.00
16	14.0	30.0	25.6	95.0	0.0301	7.6	18.9	933.	0.0763	28.8	0.00

RUN	TSKY (C)	HW "(W/SQM-C)"	UL	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	-2.7	33.1	6.10	0.92	51.0	48.8	49.5	51.7	0.0372
2	-2.7	34.6	6.13	0.92	49.6	49.1	49.3	49.8	0.0374
3	-2.3	38.0	6.17	0.92	52.1	47.5	47.8	52.5	0.0400
4	-2.3	36.1	6.17	0.92	48.0	44.9	45.4	48.4	0.0441
5	-3.6	29.6	5.93	0.92	66.8	62.3	62.7	67.2	0.0135
6	0.8	29.6	6.02	0.92	69.6	62.7	62.9	69.8	0.0132
7	6.3	29.6	6.10	0.92	67.9	63.6	63.9	68.2	0.0113
8	7.9	29.6	6.12	0.92	67.5	63.2	63.8	68.1	0.0115
9	0.8	19.4	6.34	0.92	40.8	35.1	34.9	40.5	0.0610
10	1.9	19.4	6.35	0.92	43.5	36.2	36.0	43.3	0.0591
11	3.5	19.4	6.36	0.92	43.6	36.3	36.2	43.5	0.0589
12	4.8	19.4	6.37	0.92	41.5	35.5	35.5	41.5	0.0600
13	10.2	33.1	6.86	0.91	28.9	23.2	26.5	32.2	0.0736
14	10.6	33.1	6.86	0.91	27.4	23.7	26.9	30.7	0.0730
15	11.5	34.6	6.88	0.91	28.1	23.7	27.1	31.5	0.0727
16	11.9	34.6	6.88	0.91	28.8	22.6	26.0	32.1	0.0744

COLLECTOR TEST FACILITY,G PPG

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	4.0	38.0	27.3	28.4	0.0306	3.1	11.0	1013.	0.0053	67.1	0.00
2	3.0	34.0	27.7	28.6	0.0303	4.9	10.5	1022.	0.0052	67.7	0.00
3	3.8	25.0	28.4	61.3	0.0306	4.5	9.7	1039.	0.0346	47.6	0.00
4	2.6	23.0	28.8	61.6	0.0304	5.8	9.2	1049.	0.0342	48.7	0.00
5	1.2	16.0	30.1	80.0	0.0301	4.5	9.1	1045.	0.0500	36.5	0.00
6	3.0	14.0	29.8	80.1	0.0299	0.9	9.1	1042.	0.0507	37.3	0.00
7	4.2	16.0	30.2	98.6	0.0293	5.4	8.9	1051.	0.0665	22.4	0.00
8	4.4	18.0	30.5	99.2	0.0293	3.1	9.6	1039.	0.0677	22.6	0.00
9	3.2	25.0	30.6	80.9	0.0307	2.7	10.2	1036.	0.0509	38.5	0.00
10	3.9	28.0	30.7	80.2	0.0307	4.5	10.4	1033.	0.0502	37.4	0.00
11	2.2	39.0	31.1	61.7	0.0305	5.4	11.3	1024.	0.0331	49.9	0.00
12	1.6	42.0	31.5	62.0	0.0305	4.5	11.6	1011.	0.0334	51.0	0.00
13	1.3	52.0	31.4	35.0	0.0309	5.8	14.1	988.	0.0079	68.7	0.00
14	1.8	54.0	31.2	34.9	0.0309	4.0	15.5	974.	0.0081	66.8	0.00
15	1.3	52.0	31.4	35.0	0.0309	5.8	14.1	988.	0.0079	68.7	0.00
16	1.8	54.0	31.2	34.9	0.0309	4.0	15.5	974.	0.0081	66.8	0.00

RUN	TSKY (C)	HW "(W/SQM-C)"	UL "(W/SQM-C)"	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	14.3	17.5	6.18	0.92	67.1	69.3	69.5	67.3	0.0011
2	14.9	24.3	6.17	0.92	67.7	69.5	69.6	67.8	0.0009
3	15.9	22.8	6.37	0.92	47.6	52.0	52.7	48.3	0.0317
4	16.5	27.7	6.43	0.92	48.7	52.0	52.9	49.6	0.0313
5	18.4	22.8	6.58	0.91	36.5	41.8	43.2	37.9	0.0478
6	17.9	9.1	6.26	0.92	37.3	43.4	42.8	36.7	0.0483
7	18.5	26.2	6.91	0.91	22.4	29.3	32.2	25.3	0.0651
8	18.9	17.5	6.72	0.91	22.6	30.0	31.5	24.1	0.0661
9	19.1	16.0	6.48	0.92	38.5	41.9	42.7	39.3	0.0486
10	19.2	22.8	6.59	0.92	37.4	41.5	43.1	38.9	0.0479
11	19.8	26.2	6.44	0.92	49.9	52.6	53.7	51.0	0.0299
12	20.4	22.8	6.41	0.92	51.0	52.5	53.5	52.0	0.0302
13	20.2	27.7	6.27	0.92	68.7	67.6	68.0	69.1	0.0036
14	19.9	20.9	6.28	0.92	66.8	67.4	67.9	67.4	0.0038
15	20.2	27.7	6.27	0.92	68.7	67.6	68.0	69.1	0.0036
16	19.9	20.9	6.28	0.92	66.8	67.4	67.9	67.4	0.0038

COLLECTOR TEST FACILITY,H PPG

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	11.8	31.0	18.8	34.1	0.0242	3.1	18.7	982.	0.0211	57.7	0.59
2	5.9	31.0	19.4	35.4	0.0243	3.1	18.0	1001.	0.0217	59.2	0.59
3	5.7	31.0	20.8	36.8	0.0244	4.5	18.2	1024.	0.0212	58.8	0.59
4	16.0	31.0	21.7	38.9	0.0246	2.7	19.0	988.	0.0229	57.6	0.59
5	3.9	31.0	25.6	51.7	0.0247	4.0	17.0	1024.	0.0299	47.0	0.54
6	8.6	31.0	26.7	54.2	0.0247	4.0	17.6	1021.	0.0313	47.1	0.54
7	14.5	31.0	26.4	55.3	0.0247	4.0	17.0	989.	0.0335	45.5	0.54
8	18.4	31.0	26.6	56.1	0.0247	4.0	17.3	969.	0.0347	45.2	0.54
9	15.6	31.0	20.2	69.8	0.0250	4.9	18.7	984.	0.0534	36.6	0.54
10	8.6	31.0	20.5	71.1	0.0251	5.4	21.6	992.	0.0539	32.3	0.54
11	5.5	31.0	20.1	71.6	0.0252	4.9	24.4	989.	0.0549	31.0	0.54
12	4.1	31.0	20.9	72.2	0.0252	4.9	28.2	1008.	0.0536	30.0	0.54
13	9.8	31.0	18.4	83.3	0.0254	0.9	12.6	1016.	0.0667	32.4	0.54
14	5.7	31.0	16.6	83.3	0.0254	0.5	12.3	1042.	0.0670	33.7	0.54
15	7.2	31.0	16.2	84.4	0.0255	1.3	11.2	1048.	0.0678	31.9	0.54
16	17.4	31.0	18.1	84.4	0.0255	0.9	11.5	1011.	0.0683	30.8	0.54

RUN	TSKY (C)	HW "(W/SQM-C)"	UL "(W/SQM-C)"	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	2.2	17.5	6.03	0.88	57.7	58.1	61.6	61.2	0.0156
2	3.1	17.5	6.05	0.88	59.2	58.0	61.4	62.6	0.0160
3	5.0	22.8	6.12	0.87	58.8	58.0	61.6	62.4	0.0156
4	6.3	16.0	6.08	0.88	57.6	57.1	60.6	61.1	0.0174
5	11.9	20.9	6.27	0.88	47.0	52.8	56.2	50.4	0.0255
6	13.5	20.9	6.30	0.88	47.1	51.9	55.4	50.6	0.0269
7	13.0	20.9	6.30	0.88	45.5	50.6	54.1	48.9	0.0292
8	13.3	20.9	6.30	0.88	45.2	49.9	53.4	48.7	0.0304
9	4.2	24.3	6.39	0.88	36.6	38.4	41.5	39.7	0.0504
10	4.6	26.2	6.43	0.88	32.3	37.7	41.1	35.8	0.0510
11	4.1	24.3	6.41	0.88	31.0	37.0	40.5	34.5	0.0521
12	5.2	24.3	6.43	0.88	30.0	37.2	41.2	34.0	0.0509
13	1.6	9.1	6.19	0.88	32.4	33.2	33.0	32.1	0.0639
14	-0.9	7.6	6.10	0.88	33.7	33.8	32.9	32.8	0.0640
15	-1.5	10.6	6.26	0.88	31.9	32.2	32.2	31.9	0.0651
16	1.2	9.1	6.19	0.88	30.8	32.3	31.9	30.3	0.0656

COLLECTOR TEST FACILITY,J PPG

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	11.0	25.6	20.2	50.4	0.0327	1.1	15.4	1007.	0.0339	56.7	0.50
2	4.0	25.6	21.4	52.2	0.0324	1.1	15.5	1024.	0.0340	56.4	0.50
3	4.0	25.6	21.6	52.1	0.0328	1.8	16.4	1022.	0.0337	57.0	0.50
4	11.0	25.6	23.4	52.1	0.0326	2.7	17.8	1011.	0.0321	56.5	0.50
5	12.0	21.5	18.6	72.2	0.0323	1.3	11.8	1016.	0.0555	40.4	0.50
6	2.0	21.5	19.9	72.6	0.0323	1.3	13.1	1025.	0.0542	41.1	0.50
7	2.0	21.5	20.4	72.1	0.0323	1.6	14.9	1018.	0.0537	42.8	0.50
8	11.0	21.5	17.7	72.1	0.0322	3.4	17.8	1018.	0.0560	38.4	0.50
9	12.0	21.8	20.0	83.7	0.0327	1.3	11.6	1010.	0.0663	35.4	0.50
10	2.0	21.8	20.5	83.8	0.0327	1.1	11.1	1035.	0.0661	37.1	0.50
11	2.0	21.8	21.2	83.6	0.0329	0.9	10.7	1036.	0.0652	37.8	0.50
12	11.0	21.8	22.0	83.8	0.0331	1.1	10.4	1010.	0.0645	37.4	0.50
13	12.0	15.5	20.6	95.0	0.0322	2.2	5.1	1003.	0.0763	26.9	0.50
14	2.0	15.5	21.2	95.1	0.0322	2.2	4.8	1025.	0.0760	29.9	0.50
15	2.0	15.5	21.2	95.0	0.0322	2.2	5.2	1022.	0.0759	30.4	0.50
16	11.0	15.5	22.1	95.1	0.0322	2.2	5.1	1001.	0.0749	27.7	0.50

RUN	TSKY (C)	HW "(W/SQM-C)"	UL	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	4.2	9.9	6.00	0.90	56.7	52.6	53.6	57.7	0.0300
2	5.9	9.9	6.02	0.90	56.4	52.5	53.6	57.5	0.0301
3	6.2	12.5	6.08	0.90	57.0	52.2	53.7	58.5	0.0298
4	8.7	16.0	6.17	0.90	56.5	52.5	54.5	58.5	0.0284
5	1.9	10.6	6.14	0.90	40.4	40.1	40.1	40.4	0.0528
6	3.8	10.6	6.16	0.90	41.1	40.6	40.9	41.4	0.0514
7	4.5	11.8	6.19	0.90	42.8	40.6	41.3	43.5	0.0508
8	0.7	13.6	6.37	0.89	38.4	37.7	39.6	40.3	0.0534
9	3.9	10.6	6.27	0.90	35.4	33.7	33.5	35.2	0.0631
10	4.6	9.9	6.24	0.90	37.1	35.1	34.7	36.7	0.0612
11	5.6	9.1	6.22	0.90	37.8	35.8	35.3	37.3	0.0602
12	6.8	9.9	6.25	0.90	37.4	35.1	34.7	37.1	0.0612
13	4.8	14.1	6.59	0.89	26.9	25.7	26.1	27.3	0.0742
14	5.6	14.1	6.59	0.89	29.9	27.0	27.5	30.4	0.0721
15	5.6	14.1	6.59	0.89	30.4	26.9	27.4	31.0	0.0722
16	6.9	14.1	6.59	0.89	27.7	26.5	27.0	28.2	0.0729

COLLECTOR TEST FACILITY,K PPG

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	28.7	48.0	-8.3	62.0	0.0321	4.9	16.0	751.	0.0952	22.6	0.50
2	21.1	48.0	-6.1	59.9	0.0321	5.4	16.0	827.	0.0822	33.2	0.50
3	20.7	48.0	-2.8	49.7	0.0321	2.7	15.0	811.	0.0678	43.4	0.50
4	33.4	48.0	-1.1	46.9	0.0321	2.7	16.0	700.	0.0717	42.0	0.50
5	30.8	48.0	-9.4	48.6	0.0321	2.2	16.0	719.	0.0830	31.0	0.50
6	19.4	48.0	-8.3	48.4	0.0321	1.8	16.0	827.	0.0716	40.7	0.50
7	22.6	48.0	-7.2	26.7	0.0321	2.7	18.0	827.	0.0453	58.9	0.50
8	18.8	48.0	-10.6	47.8	0.0321	2.7	18.0	883.	0.0693	45.6	0.50
9	39.5	48.0	-9.4	76.8	0.0321	1.8	18.0	681.	0.1273	7.9	0.50
10	16.1	48.0	-9.4	73.6	0.0321	4.0	17.0	899.	0.0942	26.3	0.50
11	30.5	48.0	-8.3	57.4	0.0321	4.0	17.0	785.	0.0861	32.8	0.50
12	27.1	48.0	0.6	29.2	0.0321	2.2	19.0	735.	0.0434	59.0	0.50
13	15.5	48.0	5.0	30.9	0.0321	2.7	17.0	839.	0.0358	66.6	0.50
14	30.4	48.0	8.9	30.6	0.0321	3.1	21.0	697.	0.0357	62.9	0.50
15	30.9	48.0	-12.2	73.7	0.0321	2.2	16.0	700.	0.1236	11.9	0.50
16	14.0	48.0	-9.4	78.1	0.0321	2.2	14.0	886.	0.1003	22.8	0.50

RUN	TSKY (C)	HW "(W/SQM-C)"	UL	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	-35.2	24.3	6.10	0.90	22.6	16.8	12.4	18.2	0.0936
2	-32.3	26.2	6.11	0.90	33.2	24.5	22.3	30.9	0.0798
3	-27.8	16.0	5.80	0.90	43.4	34.9	32.4	40.9	0.0647
4	-25.5	16.0	5.75	0.90	42.0	32.6	29.9	39.2	0.0686
5	-36.7	14.1	5.74	0.90	31.0	26.7	21.7	26.0	0.0807
6	-35.2	12.5	5.72	0.90	40.7	33.5	29.9	37.1	0.0686
7	-33.7	16.0	5.53	0.90	58.9	48.0	47.2	58.2	0.0410
8	-38.3	16.0	5.80	0.90	45.6	34.0	31.5	43.1	0.0661
9	-36.7	12.5	6.02	0.90	7.9	-0.9	-13.6	-4.8	0.1266
10	-36.7	20.9	6.23	0.89	26.3	16.7	13.4	22.9	0.0923
11	-35.2	20.9	5.99	0.90	32.8	22.9	19.5	29.4	0.0837
12	-23.1	14.1	5.65	0.90	59.0	48.2	48.5	59.2	0.0389
13	-17.1	16.0	5.75	0.90	66.6	52.4	53.1	67.3	0.0309
14	-11.7	17.5	5.81	0.90	62.9	51.2	53.0	64.7	0.0311
15	-40.5	14.1	6.03	0.90	11.9	1.9	-10.4	-0.3	0.1227
16	-36.7	14.1	6.12	0.90	22.8	14.6	8.6	16.8	0.0988

COLLECTOR TEST FACILITY,L PPG

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	27.7	45.0	23.9	28.9	0.0318	2.7	17.4	916.	0.0096	68.2	0.00
2	26.5	45.0	26.1	29.2	0.0318	2.7	18.5	921.	0.0075	68.9	0.00
3	25.5	45.0	26.9	29.4	0.0318	2.7	18.5	921.	0.0068	68.9	0.00
4	25.7	45.0	27.2	29.6	0.0318	4.0	17.2	923.	0.0067	69.2	0.00
5	28.1	45.0	23.9	58.4	0.0314	2.7	21.2	913.	0.0409	49.3	0.00
6	27.8	45.0	23.9	58.7	0.0314	2.7	21.1	915.	0.0410	49.7	0.00
7	28.1	45.0	23.9	58.7	0.0314	2.7	22.4	913.	0.0411	49.8	0.00
8	28.8	45.0	24.2	58.7	0.0314	2.7	25.0	909.	0.0409	49.5	0.00
9	28.8	45.0	24.4	75.1	0.0311	1.8	20.0	908.	0.0580	36.8	0.00
10	28.1	45.0	24.6	75.1	0.0311	2.7	21.2	912.	0.0577	36.6	0.00
11	27.8	45.0	24.6	75.1	0.0311	2.2	23.6	916.	0.0574	36.9	0.00
12	28.1	45.0	25.0	75.1	0.0311	4.9	23.0	913.	0.0571	36.6	0.00
13	29.1	45.0	26.1	65.0	0.0313	3.1	21.6	892.	0.0463	43.7	0.00
14	28.4	45.0	26.4	65.1	0.0313	3.1	21.6	899.	0.0457	44.4	0.00
15	28.1	45.0	26.7	65.1	0.0313	2.7	20.2	903.	0.0452	44.2	0.00
16	28.4	45.0	26.7	65.1	0.0313	2.9	20.2	901.	0.0453	44.8	0.00

RUN	TSKY (C)	HW "(W/SQM-C)"	UL	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	9.5	16.0	6.10	0.92	68.2	66.2	67.1	69.1	0.0055
2	12.6	16.0	6.15	0.92	68.9	67.2	68.2	69.9	0.0034
3	13.7	16.0	6.17	0.92	68.9	67.6	68.5	69.8	0.0027
4	14.2	20.9	6.15	0.92	69.2	67.8	68.6	70.0	0.0026
5	9.5	16.0	6.19	0.92	49.3	47.9	49.1	50.5	0.0378
6	9.5	16.0	6.19	0.92	49.7	47.8	49.0	50.9	0.0380
7	9.5	16.0	6.19	0.92	49.8	47.6	48.9	51.1	0.0381
8	9.9	16.0	6.19	0.92	49.5	47.5	49.0	51.0	0.0380
9	10.2	12.5	6.26	0.92	36.8	37.6	38.1	37.3	0.0558
10	10.5	16.0	6.34	0.92	36.6	37.3	38.4	37.7	0.0554
11	10.5	14.1	6.30	0.92	36.9	37.5	38.6	38.0	0.0551
12	11.0	24.3	6.47	0.92	36.6	36.6	38.7	38.8	0.0549
13	12.6	17.5	6.29	0.92	43.7	44.1	45.7	45.2	0.0436
14	13.0	17.5	6.29	0.92	44.4	44.5	46.0	45.9	0.0430
15	13.5	16.0	6.27	0.92	44.2	45.0	46.3	45.5	0.0425
16	13.5	16.7	6.29	0.92	44.8	44.9	46.3	46.2	0.0426

COLLECTOR TEST FACILITY,M PPG

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	19.0	40.0	25.9	22.2	0.0314	0.4	12.0	1067.	0.0010	73.0	0.00
2	15.0	40.0	26.2	22.3	0.0314	0.4	13.0	1082.	0.0009	74.0	0.00
3	15.0	40.0	26.8	22.3	0.0314	0.5	14.0	1087.	0.0005	75.0	0.00
4	19.0	40.0	27.3	22.3	0.0314	0.2	13.0	1074.	0.0000	76.0	0.00
5	20.0	40.0	25.8	45.6	0.0311	0.1	14.0	1056.	0.0225	61.0	0.00
6	16.0	40.0	26.6	45.7	0.0311	0.1	14.0	1069.	0.0217	61.0	0.00
7	16.0	40.0	28.0	45.8	0.0311	0.1	13.0	1071.	0.0206	62.0	0.00
8	20.0	40.0	28.3	45.8	0.0311	0.1	13.0	1067.	0.0204	65.0	0.00
9	21.0	40.0	23.0	55.6	0.0313	0.1	16.0	1021.	0.0353	55.0	0.00
10	17.0	40.0	23.5	55.7	0.0313	0.3	16.0	1034.	0.0346	56.0	0.00
11	17.0	40.0	24.8	54.7	0.0320	0.1	18.0	1021.	0.0328	58.0	0.00
12	21.0	40.0	25.2	54.6	0.0320	0.1	17.0	1011.	0.0326	58.0	0.00
13	23.0	40.0	26.1	63.8	0.0321	0.2	22.0	1035.	0.0396	53.0	0.00
14	19.0	40.0	26.7	64.2	0.0320	0.3	21.0	1045.	0.0391	54.0	0.00
15	19.0	40.0	27.0	63.9	0.0320	0.2	21.0	1065.	0.0378	52.0	0.00
16	23.0	40.0	27.5	63.2	0.0321	0.2	18.0	964.	0.0401	52.0	0.00

RUN	TSKY (C)	HW "(W/SQM-C)"	UL "(W/SQM-C)"	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	12.3	7.2	6.10	0.92	73.0	71.7	71.9	73.2	-0.0035
2	12.7	7.2	6.10	0.92	74.0	71.8	72.0	74.2	-0.0036
3	13.6	7.6	6.12	0.92	75.0	72.0	72.3	75.3	-0.0041
4	14.3	6.5	6.13	0.92	76.0	72.3	72.6	76.3	-0.0047
5	12.2	6.1	5.97	0.92	61.0	60.2	59.9	60.7	0.0188
6	13.3	6.1	5.98	0.92	61.0	60.7	60.4	60.7	0.0179
7	15.3	6.1	6.01	0.92	62.0	61.4	61.1	61.7	0.0166
8	15.8	6.1	6.01	0.92	65.0	61.4	61.2	64.7	0.0164
9	8.2	6.1	5.92	0.92	55.0	53.2	52.5	54.3	0.0319
10	8.9	6.8	5.96	0.92	56.0	53.5	53.0	55.5	0.0311
11	10.7	6.1	5.94	0.92	58.0	54.5	54.0	57.6	0.0293
12	11.3	6.1	5.95	0.92	58.0	54.6	54.1	57.6	0.0291
13	12.6	6.5	6.00	0.92	53.0	50.0	49.9	52.9	0.0364
14	13.5	6.8	6.02	0.92	54.0	50.4	50.2	53.9	0.0359
15	13.9	6.5	6.01	0.92	52.0	51.1	51.0	51.8	0.0346
16	14.6	6.5	6.01	0.92	52.0	50.0	49.6	51.6	0.0370

COLLECTOR TEST FACILITY,N PPG

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	11.0	25.0	16.2	50.5	0.0315	2.9	15.1	1017.	0.0373	50.4	0.50
2	7.4	25.0	17.8	50.9	0.0313	3.0	12.2	1083.	0.0342	49.3	0.50
3	7.4	25.0	17.8	49.9	0.0315	3.1	10.7	1081.	0.0332	49.2	0.50
4	11.0	25.0	18.6	50.5	0.0317	2.9	10.2	1073.	0.0334	50.3	0.50
5	12.2	25.0	21.4	93.7	0.0316	1.6	12.5	1027.	0.0717	16.7	0.50
6	9.1	25.0	22.0	93.9	0.0318	2.0	12.4	1034.	0.0708	17.4	0.50
7	9.1	25.0	22.2	94.7	0.0316	3.5	12.3	1042.	0.0708	17.8	0.50
8	12.2	25.0	22.2	94.5	0.0317	1.5	11.8	1031.	0.0716	19.7	0.50
9	12.3	25.0	23.0	38.5	0.0319	3.0	14.0	1031.	0.0193	58.2	0.50
10	9.3	25.0	24.0	38.4	0.0318	2.8	13.5	1046.	0.0181	58.8	0.50
11	9.3	25.0	24.5	38.7	0.0321	2.6	14.0	1041.	0.0180	60.1	0.50
12	12.3	25.0	24.7	38.6	0.0361	2.7	15.7	1013.	0.0183	60.6	0.50
13	18.0	25.0	25.0	79.4	0.0320	0.9	11.9	956.	0.0592	32.2	0.50
14	14.2	25.0	27.2	79.4	0.0318	0.7	21.1	994.	0.0550	35.6	0.50
15	14.2	25.0	28.6	79.4	0.0319	0.7	31.6	1001.	0.0533	37.2	0.50
16	18.0	25.0	30.0	79.2	0.0319	0.7	34.6	1040.	0.0499	37.2	0.50

RUN	TSKY (C)	HW "(W/SQM-C)"	UL	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	-1.5	16.7	6.07	0.90	50.4	50.1	51.5	51.8	0.0337
2	0.8	17.1	6.10	0.89	49.3	51.9	53.3	50.7	0.0306
3	0.8	17.5	6.10	0.90	49.2	52.5	53.8	50.5	0.0297
4	1.9	16.7	6.10	0.90	50.3	52.6	53.8	51.5	0.0297
5	5.9	11.8	6.44	0.89	16.7	28.4	28.7	17.0	0.0704
6	6.8	13.3	6.51	0.89	17.4	28.4	29.2	18.2	0.0695
7	7.0	19.0	6.70	0.89	17.8	26.9	29.2	20.1	0.0696
8	7.0	11.4	6.43	0.89	19.7	28.7	28.8	19.9	0.0701
9	8.2	17.1	6.11	0.89	58.2	60.0	61.9	60.1	0.0150
10	9.6	16.3	6.12	0.89	58.8	60.8	62.6	60.6	0.0138
11	10.3	15.6	6.12	0.90	60.1	60.8	62.7	61.9	0.0136
12	10.6	16.0	6.12	0.90	60.6	60.9	62.6	62.3	0.0137
13	11.0	9.1	6.21	0.90	32.2	37.4	37.5	32.2	0.0569
14	14.2	8.4	6.20	0.90	35.6	39.2	40.2	36.6	0.0525
15	16.2	8.4	6.22	0.90	37.2	39.2	41.3	39.3	0.0507
16	18.2	8.4	6.23	0.89	37.2	40.8	43.4	39.8	0.0473

COLLECTOR TEST FACILITY,0 PPG

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	53.1	60.3	15.0	37.7	0.0332	2.2	23.1	651.	0.0381	48.1	0.44
2	44.2	60.3	15.8	38.5	0.0332	3.6	20.0	784.	0.0325	52.9	0.44
3	48.9	60.3	25.7	37.9	0.0331	1.8	19.6	793.	0.0192	56.2	0.44
4	55.2	60.3	23.9	38.0	0.0330	3.6	24.0	650.	0.0252	51.9	0.44
5	43.2	60.3	25.6	54.9	0.0335	1.8	10.7	792.	0.0402	46.9	0.44
6	40.1	60.3	26.0	53.1	0.0326	2.7	14.2	833.	0.0360	50.1	0.44
7	39.9	60.3	26.1	55.2	0.0334	2.7	15.7	815.	0.0391	51.9	0.44
8	42.6	60.3	27.6	54.7	0.0334	2.7	10.9	760.	0.0389	50.8	0.44
9	43.8	60.3	15.3	70.7	0.0333	2.2	14.4	786.	0.0724	27.8	0.44
10	40.6	60.3	15.8	71.3	0.0345	1.8	15.5	818.	0.0699	33.7	0.44
11	40.6	60.3	16.1	68.5	0.0333	2.2	11.6	817.	0.0665	37.0	0.44
12	43.8	60.3	16.9	69.7	0.0338	2.2	14.7	773.	0.0704	32.7	0.44
13	45.1	60.3	21.4	29.2	0.0296	2.7	18.6	800.	0.0141	58.2	0.44
14	42.7	60.3	22.5	29.7	0.0337	1.8	14.3	826.	0.0128	61.2	0.44
15	42.5	60.3	22.6	30.1	0.0340	2.2	15.9	838.	0.0129	60.7	0.44
16	44.7	60.3	22.5	30.3	0.0339	1.8	16.1	803.	0.0107	61.0	0.44

RUN	TSKY (C)	HW "(W/SQM-C)"	UL "(W/SQM-C)"	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	-3.1	14.1	5.92	0.90	48.1	45.1	50.8	53.8	0.0349
2	-2.0	19.4	5.98	0.90	52.9	50.7	54.2	56.4	0.0290
3	12.0	12.5	6.11	0.90	56.2	56.6	61.7	61.3	0.0154
4	9.5	19.4	6.12	0.90	51.9	50.5	58.3	59.7	0.0217
5	11.9	12.5	6.13	0.90	46.9	46.9	49.6	49.6	0.0370
6	12.5	16.0	6.19	0.90	50.1	49.3	52.2	53.0	0.0325
7	12.6	16.0	6.20	0.90	51.9	47.5	50.3	54.8	0.0357
8	14.8	16.0	6.21	0.90	50.8	47.3	50.4	53.8	0.0357
9	-2.7	14.1	6.14	0.90	27.8	28.2	28.6	28.2	0.0705
10	-2.0	12.5	6.12	0.90	33.7	30.3	30.4	33.7	0.0678
11	-1.6	14.1	6.14	0.90	37.0	32.4	32.8	37.4	0.0641
12	-0.5	14.1	6.15	0.90	32.7	29.3	30.1	33.5	0.0683
13	5.9	16.0	6.05	0.90	58.2	60.3	64.8	62.6	0.0098
14	7.5	12.5	6.06	0.90	61.2	62.0	65.3	64.5	0.0087
15	7.6	14.1	6.07	0.90	60.7	61.8	65.2	64.1	0.0089
16	7.5	12.5	6.06	0.90	61.0	61.0	64.8	64.8	0.0097

COLLECTOR TEST FACILITY,R PPG

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	15.7	45.0	13.0	20.8	0.0317	6.1	10.0	974.	0.0122	70.0	0.00
2	14.7	45.0	12.0	20.9	0.0317	6.3	10.0	974.	0.0134	71.0	0.00
3	14.6	45.0	13.0	21.1	0.0315	6.7	10.0	974.	0.0126	71.0	0.00
4	15.4	45.0	13.0	21.4	0.0316	6.3	10.0	966.	0.0130	72.0	0.00
5	8.2	30.0	19.0	86.5	0.0314	3.0	9.0	920.	0.0754	40.0	0.00
6	6.0	30.0	19.0	86.2	0.0314	4.9	9.0	930.	0.0740	40.0	0.00
7	5.6	30.0	19.0	86.0	0.0316	3.8	9.0	930.	0.0744	38.0	0.00
8	7.3	30.0	19.0	86.3	0.0314	3.5	9.0	930.	0.0748	40.0	0.00
9	9.3	30.0	20.0	44.2	0.0316	6.8	10.0	921.	0.0300	62.0	0.00
10	7.4	30.0	20.0	44.1	0.0317	8.7	10.0	930.	0.0297	63.0	0.00
11	7.1	30.0	21.0	44.4	0.0317	9.6	10.0	930.	0.0289	62.0	0.00
12	8.5	30.0	21.0	44.1	0.0315	10.7	10.0	930.	0.0286	63.0	0.00
13	5.9	20.0	23.0	24.6	0.0317	9.8	13.0	921.	0.0062	76.0	0.00
14	2.5	20.0	23.0	24.9	0.0317	10.3	13.0	930.	0.0066	76.0	0.00
15	1.4	20.0	23.0	24.8	0.0316	9.8	13.0	921.	0.0066	77.0	0.00
16	4.8	20.0	23.0	25.1	0.0317	8.9	13.0	930.	0.0068	76.0	0.00

RUN	TSKY (C)	HW "(W/SQM-C)"	UL	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	-6.0	28.9	5.87	0.92	70.0	66.0	65.7	69.7	0.0080
2	-7.4	29.6	5.86	0.92	71.0	65.4	65.1	70.7	0.0091
3	-6.0	31.2	5.88	0.92	71.0	65.8	65.5	70.7	0.0083
4	-6.0	29.6	5.88	0.92	72.0	65.6	65.3	71.7	0.0087
5	2.5	17.1	6.46	0.92	40.0	27.4	26.7	39.3	0.0734
6	2.5	24.3	6.61	0.92	40.0	26.8	27.4	40.6	0.0723
7	2.5	20.1	6.53	0.92	38.0	27.6	27.6	37.9	0.0720
8	2.5	19.0	6.51	0.92	40.0	27.6	27.3	39.7	0.0724
9	3.9	31.5	6.15	0.92	62.0	55.5	55.7	62.2	0.0263
10	3.9	38.8	6.18	0.92	63.0	55.6	55.9	63.3	0.0259
11	5.3	42.2	6.21	0.92	62.0	56.0	56.4	62.4	0.0252
12	5.3	46.4	6.21	0.92	63.0	56.1	56.5	63.4	0.0248
13	8.2	42.9	6.07	0.92	76.0	68.9	69.1	76.1	0.0017
14	8.2	44.8	6.07	0.92	76.0	68.8	68.9	76.1	0.0020
15	8.2	42.9	6.07	0.92	77.0	68.8	68.9	77.1	0.0020
16	8.2	39.5	6.07	0.92	76.0	68.6	68.8	76.1	0.0023

COLLECTOR TEST FACILITY,E CHAMBERLAIN

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	16.4	50.0	24.0	29.5	0.0185	2.0	16.5	945.	0.0151	73.1	0.00
2	15.4	50.0	24.9	29.4	0.0185	1.3	17.0	949.	0.0139	73.0	0.00
3	15.9	50.0	24.7	29.4	0.0186	1.3	17.7	951.	0.0142	73.9	0.00
4	16.5	50.0	24.9	31.9	0.0186	0.8	17.9	947.	0.0157	65.9	0.00
5	14.2	50.0	28.1	53.5	0.0178	1.3	12.8	897.	0.0354	53.9	0.00
6	13.0	50.0	27.9	53.8	0.0173	1.3	12.5	904.	0.0347	62.9	0.00
7	13.3	50.0	28.0	54.1	0.0171	2.0	11.7	932.	0.0364	61.7	0.00
8	14.6	50.0	28.2	53.7	0.0173	2.6	11.3	943.	0.0357	63.8	0.00
9	4.5	50.0	21.6	81.6	0.0163	2.2	21.3	908.	0.0708	32.3	0.00
10	3.0	50.0	20.9	82.5	0.0161	2.9	20.5	911.	0.0736	40.6	0.00
11	4.5	50.0	21.4	84.1	0.0154	2.3	20.8	912.	0.0746	37.9	0.00
12	6.0	50.0	21.9	84.4	0.0145	2.2	22.6	908.	0.0753	40.0	0.00
13	5.0	50.0	23.4	73.7	0.0176	3.9	15.8	926.	0.0604	45.3	0.00
14	3.5	50.0	23.9	74.4	0.0181	4.4	15.9	924.	0.0608	47.6	0.00
15	3.3	50.0	23.4	74.2	0.0180	4.2	15.8	920.	0.0618	50.9	0.00
16	5.0	50.0	24.1	74.7	0.0178	4.0	16.0	913.	0.0617	47.6	0.00

RUN	TSKY (C)	HW "(W/SQM-C)"	UL "(W/SQM-C)"	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	9.6	13.3	4.50	0.93	73.1	76.4	78.2	74.9	0.0058
2	10.9	10.6	4.36	0.93	73.0	77.2	78.7	74.5	0.0047
3	10.6	10.6	4.36	0.93	73.9	77.1	78.6	75.5	0.0049
4	10.9	8.7	4.27	0.93	65.9	76.4	77.5	67.0	0.0074
5	15.5	10.6	4.63	0.92	53.9	67.0	67.2	54.1	0.0283
6	15.2	10.6	4.64	0.92	62.9	66.8	67.0	63.2	0.0287
7	15.3	13.3	4.82	0.92	61.7	66.3	67.4	62.8	0.0280
8	15.6	15.6	4.93	0.92	63.8	66.3	67.9	65.4	0.0270
9	6.2	14.1	5.18	0.91	32.3	46.3	46.6	32.6	0.0661
10	5.2	16.7	5.35	0.91	40.6	44.4	45.7	42.0	0.0676
11	5.9	14.4	5.23	0.91	37.9	44.5	45.1	38.4	0.0687
12	6.6	14.1	5.21	0.90	40.0	44.4	45.0	40.7	0.0688
13	8.7	20.5	5.40	0.91	45.3	51.0	53.2	47.6	0.0543
14	9.5	22.4	5.47	0.91	47.6	50.5	53.1	50.2	0.0547
15	8.7	21.7	5.44	0.91	50.9	50.3	52.7	53.3	0.0552
16	9.7	20.9	5.42	0.91	47.6	50.3	52.6	49.9	0.0554

COLLECTOR TEST FACILITY,G CHAMBERLAIN

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	0.0	39.3	33.2	32.8	0.0359	2.2	11.3	991.	0.0048	84.0	0.00
2	0.0	36.9	32.8	32.5	0.0359	3.1	11.1	1000.	0.0046	84.2	0.00
3	0.0	30.8	33.5	58.3	0.0351	3.1	10.7	1015.	0.0287	71.5	0.00
4	0.0	29.3	33.1	58.3	0.0351	4.5	10.8	1015.	0.0291	71.5	0.00
5	0.0	25.7	33.9	77.3	0.0352	0.9	10.7	1018.	0.0463	62.1	0.00
6	0.0	25.6	33.8	77.2	0.0353	1.8	10.9	1017.	0.0465	62.4	0.00
7	0.0	38.6	34.2	76.7	0.0356	4.9	12.8	1009.	0.0460	65.1	0.00
8	0.0	41.3	34.3	76.5	0.0360	4.9	13.1	1006.	0.0458	64.6	0.00
9	0.0	47.9	34.5	57.4	0.0364	4.9	15.5	986.	0.0275	73.0	0.00
10	0.0	51.0	34.2	56.9	0.0365	4.5	3.3	1021.	0.0264	72.3	0.00
11	0.0	26.5	36.2	105.9	0.0350	0.9	13.0	1008.	0.0720	46.8	0.00
12	0.0	27.3	36.6	105.8	0.0350	1.3	12.8	1008.	0.0713	45.8	0.00
13	0.0	28.0	36.8	105.9	0.0346	3.1	13.1	1012.	0.0712	46.3	0.00
14	0.0	30.6	36.8	106.0	0.0345	3.6	13.4	1013.	0.0710	44.9	0.00
15	0.0	37.3	37.0	37.6	0.0354	4.5	15.6	1003.	0.0056	83.1	0.00
16	0.0	39.8	38.0	37.1	0.0356	2.7	16.5	998.	0.0041	82.7	0.00

RUN	TSKY (C)	HW "(W/SQM-C)"	UL	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	22.8	14.1	4.33	0.95	84.0	81.5	81.0	83.5	-0.0004
2	22.3	17.5	4.45	0.95	84.2	81.3	80.9	83.8	-0.0003
3	23.3	17.5	5.11	0.94	71.5	69.0	69.2	71.6	0.0244
4	22.7	22.8	5.30	0.94	71.5	68.2	69.0	72.3	0.0248
5	23.8	9.1	4.79	0.95	62.1	62.3	59.6	59.5	0.0426
6	23.7	12.5	5.10	0.95	62.4	60.6	59.6	61.4	0.0427
7	24.3	24.3	5.55	0.94	65.1	58.3	59.9	66.7	0.0421
8	24.4	24.3	5.52	0.94	64.6	58.5	60.0	66.1	0.0419
9	24.7	24.3	5.13	0.95	73.0	69.2	69.8	73.6	0.0232
10	24.3	22.8	5.07	0.95	72.3	70.7	70.3	71.9	0.0222
11	27.2	9.1	4.99	0.95	46.8	48.8	44.8	42.9	0.0691
12	27.8	10.6	5.16	0.95	45.8	47.7	45.1	43.2	0.0687
13	28.1	17.5	5.68	0.94	46.3	44.0	45.3	47.6	0.0683
14	28.1	19.4	5.76	0.94	44.9	43.3	45.3	46.9	0.0683
15	28.4	22.8	4.58	0.95	83.1	80.4	80.5	83.2	0.0006
16	29.8	16.0	4.31	0.95	82.7	81.3	81.2	82.6	-0.0009

COLLECTOR TEST FACILITY,H CHAMBERLAIN

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	6.0	40.0	22.8	35.0	0.0364	1.3	10.6	967.	0.0181	75.4	0.50
2	6.0	40.0	23.3	35.6	0.0364	1.8	10.6	964.	0.0181	75.5	0.50
3	6.0	40.0	23.3	35.6	0.0364	1.3	11.2	968.	0.0181	75.7	0.50
4	6.0	40.0	24.2	36.1	0.0364	1.6	11.2	963.	0.0180	75.7	0.50
5	6.0	40.0	14.4	47.6	0.0368	1.6	15.5	968.	0.0389	65.2	0.50
6	6.0	40.0	14.4	47.6	0.0368	1.3	14.9	1008.	0.0375	65.1	0.50
7	6.0	40.0	15.0	43.1	0.0368	1.3	15.9	934.	0.0350	70.1	0.50
8	6.0	40.0	16.7	43.3	0.0369	1.3	14.7	999.	0.0315	69.6	0.50
9	6.0	40.0	17.8	69.2	0.0375	3.1	9.6	1004.	0.0551	56.5	0.50
10	6.0	40.0	18.1	68.8	0.0375	3.1	9.6	1004.	0.0546	58.4	0.50
11	6.0	40.0	18.6	70.0	0.0375	3.1	9.8	1000.	0.0551	55.1	0.50
12	6.0	40.0	18.9	69.4	0.0375	2.7	10.0	1000.	0.0544	58.6	0.50
13	6.0	40.0	12.3	85.8	0.0379	4.0	11.6	1018.	0.0752	45.6	0.50
14	6.0	40.0	12.4	85.4	0.0379	4.5	11.6	1010.	0.0754	46.2	0.50
15	6.0	40.0	13.2	90.3	0.0381	3.6	11.2	1018.	0.0785	44.2	0.50
16	6.0	40.0	12.8	90.6	0.0381	4.0	11.3	1006.	0.0801	41.1	0.50

RUN	TSKY (C)	HW "(W/SQM-C)"	UL	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	7.9	10.6	4.53	0.93	75.4	74.8	75.0	75.6	0.0126
2	8.6	12.5	4.64	0.93	75.5	74.4	75.0	76.1	0.0128
3	8.6	10.6	4.53	0.93	75.7	74.7	75.0	76.0	0.0127
4	9.9	11.8	4.59	0.93	75.7	74.7	75.2	76.2	0.0124
5	-4.0	11.8	4.84	0.93	65.2	64.1	64.1	65.1	0.0343
6	-4.0	10.6	4.75	0.93	65.1	65.2	64.8	64.7	0.0329
7	-3.1	10.6	4.70	0.93	70.1	66.5	66.3	69.8	0.0301
8	-0.8	10.6	4.69	0.93	69.6	68.2	68.1	69.5	0.0266
9	0.8	17.5	5.37	0.93	56.5	53.9	55.0	57.6	0.0512
10	1.2	17.5	5.37	0.93	58.4	54.3	55.4	59.5	0.0505
11	1.9	17.5	5.37	0.93	55.1	53.8	54.9	56.2	0.0514
12	2.4	16.0	5.29	0.93	58.6	54.7	55.4	59.2	0.0505
13	-6.9	20.9	5.72	0.92	45.6	40.8	43.1	47.9	0.0722
14	-6.8	22.8	5.79	0.92	46.2	40.2	43.0	49.0	0.0723
15	-5.7	19.4	5.69	0.92	44.2	39.2	41.0	46.0	0.0757
16	-6.2	20.9	5.76	0.92	41.1	37.8	40.1	43.4	0.0773

COLLECTOR TEST FACILITY,J CHAMBERLAIN

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	1.3	37.4	25.9	57.8	0.0354	1.1	6.5	1017.	0.0360	68.3	0.50
2	1.8	37.4	26.2	57.9	0.0354	1.0	7.4	953.	0.0360	68.3	0.50
3	1.6	38.0	22.8	82.7	0.0354	0.9	13.9	970.	0.0650	54.1	0.50
4	3.9	38.0	22.9	84.0	0.0354	0.9	13.5	969.	0.0670	53.5	0.50
5	1.8	45.1	29.6	35.0	0.0353	1.0	8.7	986.	0.0110	76.3	0.50
6	2.9	45.1	30.2	35.1	0.0353	0.8	7.4	989.	0.0110	78.1	0.50
7	1.9	45.4	26.2	94.5	0.0353	0.8	8.7	1001.	0.0720	51.2	0.50
8	2.9	45.4	26.7	94.8	0.0353	1.1	9.5	1001.	0.0720	50.4	0.50
9	1.8	47.0	21.7	70.6	0.0353	1.0	22.3	933.	0.0570	59.2	0.50
10	2.3	47.0	21.5	70.6	0.0353	0.9	21.2	941.	0.0560	59.2	0.50
11	1.5	48.0	23.0	46.9	0.0353	0.9	16.9	900.	0.0320	69.8	0.50
12	2.3	48.0	22.1	46.7	0.0353	1.7	18.4	906.	0.0320	70.2	0.50
13	1.3	49.5	20.0	24.5	0.0353	1.8	12.2	980.	0.0100	76.9	0.50
14	2.3	49.5	20.2	24.5	0.0353	1.9	11.4	978.	0.0100	76.6	0.50
15	11.2	47.0	20.6	70.3	0.0353	0.6	23.1	886.	0.0600	57.4	0.50
16	9.1	47.0	22.2	70.9	0.0353	0.7	20.4	939.	0.0560	59.4	0.50

RUN	TSKY (C)	HW "(W/SQM-C)"	UL "(W/SQM-C)"	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	12.3	9.9	4.71	0.93	68.3	66.6	65.6	67.3	0.0314
2	12.7	9.5	4.68	0.93	68.3	65.9	64.6	67.1	0.0333
3	7.9	9.1	4.84	0.93	54.1	52.1	49.1	51.1	0.0618
4	8.0	9.1	4.85	0.93	53.5	51.5	48.3	50.4	0.0631
5	17.6	9.5	4.33	0.94	76.3	78.2	78.4	76.5	0.0055
6	18.5	8.7	4.27	0.94	78.1	78.6	78.6	78.1	0.0050
7	12.7	8.7	4.82	0.93	51.2	49.7	45.4	46.9	0.0682
8	13.5	9.9	4.95	0.93	50.4	48.7	45.5	47.1	0.0680
9	6.3	9.5	4.74	0.93	59.2	56.2	54.3	57.3	0.0524
10	6.0	9.1	4.70	0.93	59.2	56.6	54.4	57.0	0.0522
11	8.2	9.1	4.49	0.93	69.8	68.7	68.1	69.2	0.0266
12	6.9	12.2	4.72	0.93	70.2	67.4	67.8	70.6	0.0272
13	3.9	12.5	4.43	0.93	76.9	77.9	78.8	77.7	0.0046
14	4.2	12.9	4.45	0.93	76.6	78.0	78.9	77.4	0.0044
15	4.8	8.0	4.57	0.93	57.4	55.7	52.2	54.0	0.0561
16	7.0	8.4	4.62	0.93	59.4	57.4	54.6	56.6	0.0519

COLLECTOR TEST FACILITY,L CHAMBERLAIN

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	9.6	45.0	29.6	65.4	0.0371	0.5	17.8	930.	0.0426	68.0	0.00
2	9.4	45.0	29.9	65.3	0.0371	0.5	17.8	926.	0.0424	69.3	0.00
3	9.4	45.0	30.5	65.4	0.0371	0.5	19.2	925.	0.0418	68.9	0.00
4	9.6	45.0	30.6	65.4	0.0371	0.5	19.2	922.	0.0419	69.1	0.00
5	9.2	45.0	31.1	44.6	0.0374	3.1	22.8	922.	0.0193	79.0	0.00
6	9.0	45.0	31.1	44.4	0.0375	0.7	21.0	928.	0.0192	81.6	0.00
7	9.0	45.0	30.7	44.3	0.0375	0.7	20.5	931.	0.0193	80.3	0.00
8	9.2	45.0	30.4	44.2	0.0375	2.5	21.9	933.	0.0196	80.7	0.00
9	7.0	45.0	29.2	75.1	0.0369	0.7	16.6	977.	0.0507	61.1	0.00
10	6.8	45.0	29.3	75.2	0.0369	0.7	14.1	971.	0.0510	60.4	0.00
11	6.8	45.0	28.6	75.3	0.0369	1.8	15.2	972.	0.0517	60.8	0.00
12	7.0	45.0	28.4	75.3	0.0369	1.1	15.2	973.	0.0518	61.2	0.00
13	6.3	45.0	35.5	87.4	0.0366	0.7	16.8	962.	0.0575	57.1	0.00
14	6.0	45.0	35.3	87.5	0.0366	0.7	16.8	965.	0.0577	58.4	0.00
15	6.0	45.0	35.6	87.4	0.0366	0.7	21.9	965.	0.0574	59.8	0.00
16	6.3	45.0	35.6	87.3	0.0366	0.7	21.9	970.	0.0570	58.6	0.00

RUN	TSKY (C)	HW "(W/SQM-C)"	UL	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	17.6	7.6	4.44	0.95	68.0	65.3	61.9	64.6	0.0385
2	18.1	7.6	4.44	0.95	69.3	65.4	62.0	65.9	0.0382
3	18.9	7.6	4.43	0.95	68.9	65.5	62.3	65.6	0.0377
4	19.1	7.6	4.43	0.95	69.1	65.5	62.3	65.8	0.0377
5	19.8	17.5	4.77	0.95	79.0	73.7	74.1	79.4	0.0146
6	19.8	8.4	4.29	0.95	81.6	75.3	74.2	80.5	0.0143
7	19.2	8.4	4.30	0.95	80.3	75.3	74.1	79.1	0.0146
8	18.8	15.2	4.70	0.95	80.7	73.9	74.0	80.8	0.0148
9	17.1	8.4	4.61	0.95	61.1	60.9	57.3	57.5	0.0470
10	17.2	8.4	4.61	0.95	60.4	60.9	57.1	56.6	0.0473
11	16.2	12.5	5.00	0.95	60.8	58.3	56.7	59.2	0.0480
12	15.9	9.9	4.78	0.95	61.2	59.5	56.6	58.3	0.0482
13	26.2	8.4	4.67	0.95	57.1	57.5	53.4	53.0	0.0540
14	25.9	8.4	4.67	0.95	58.4	57.5	53.4	54.3	0.0541
15	26.3	8.4	4.67	0.95	59.8	57.3	53.6	56.1	0.0537
16	26.3	8.4	4.67	0.95	58.6	57.5	53.8	54.9	0.0533

COLLECTOR TEST FACILITY,M CHAMBERLAIN

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	25.0	35.0	30.3	29.1	0.0325	1.4	27.0	929.	0.0040	79.8	0.00
2	27.0	35.0	30.3	29.1	0.0325	1.4	28.0	917.	0.0040	80.8	0.00
3	26.0	35.0	30.3	29.1	0.0325	1.4	28.0	923.	0.0040	80.4	0.00
4	2.5	35.0	32.8	35.7	0.0302	0.3	25.0	1110.	0.0080	76.0	0.00
5	6.0	35.0	33.3	49.6	0.0340	0.5	24.0	933.	0.0220	72.0	0.00
6	3.5	35.0	33.4	49.4	0.0340	0.5	23.0	1049.	0.0200	76.0	0.00
7	2.5	35.0	30.4	47.3	0.0333	0.9	27.0	964.	0.0220	68.9	0.00
8	6.5	35.0	30.0	39.9	0.0325	1.0	28.0	971.	0.0150	72.9	0.00
9	8.5	35.0	33.4	60.6	0.0302	0.1	23.0	1064.	0.0300	63.0	0.00
10	11.5	35.0	30.8	53.1	0.0325	0.5	22.0	840.	0.0310	67.0	0.00
11	3.5	35.0	33.5	66.1	0.0302	0.3	27.0	1141.	0.0330	63.0	0.00
12	5.0	35.0	28.6	57.6	0.0336	1.3	27.0	906.	0.0360	62.6	0.00
13	23.5	35.0	25.4	60.0	0.0340	0.8	30.0	710.	0.0520	52.2	0.00
14	22.0	35.0	25.0	60.3	0.0340	0.9	28.0	758.	0.0500	55.6	0.00
15	20.0	35.0	26.5	60.7	0.0340	1.0	29.0	788.	0.0470	56.1	0.00
16	18.0	35.0	26.3	60.6	0.0340	1.5	29.0	811.	0.0460	60.0	0.00

RUN	TSKY (C)	HW "(W/SQM-C)"	UL "(W/SQM-C)"	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	18.6	11.0	4.24	0.95	79.8	80.5	81.3	80.6	-0.0013
2	18.6	11.0	4.23	0.95	80.8	80.4	81.3	81.7	-0.0013
3	18.6	11.0	4.24	0.95	80.4	80.4	81.3	81.3	-0.0013
4	22.3	6.8	+.12	0.95	76.0	79.6	79.6	76.0	0.0026
5	23.0	7.6	4.32	0.95	72.0	73.7	72.7	70.9	0.0175
6	23.1	7.6	4.33	0.95	76.0	74.7	73.8	75.1	0.0153
7	18.8	9.1	4.47	0.95	68.9	73.0	72.6	68.6	0.0175
8	18.2	9.5	4.41	0.95	72.9	76.0	76.2	73.1	0.0102
9	23.1	6.1	4.24	0.95	63.0	70.7	68.6	60.9	0.0256
10	19.4	7.6	4.37	0.95	67.0	69.9	68.1	65.2	0.0265
11	23.3	6.8	4.40	0.95	63.0	68.7	67.1	61.4	0.0286
12	16.2	10.6	4.73	0.95	62.6	65.9	65.3	62.0	0.0320
13	11.6	8.7	4.59	0.95	52.2	59.0	56.3	49.5	0.0487
14	11.0	9.1	4.64	0.95	55.6	59.8	57.5	53.3	0.0466
15	13.2	9.5	4.67	0.95	56.1	61.0	59.2	54.3	0.0434
16	12.9	11.4	4.84	0.95	60.0	60.6	59.8	59.2	0.0423

COLLECTOR TEST FACILITY,N CHAMBERLAIN

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	8.1	60.0	-1.4	48.5	0.0351	0.8	3.3	1004.	0.0538	64.3	0.20
2	4.0	60.0	-0.6	49.5	0.0354	0.6	3.6	1009.	0.0534	59.8	0.20
3	4.0	60.0	-0.4	49.3	0.0352	0.8	3.9	1015.	0.0530	63.9	0.20
4	8.1	60.0	0.0	50.9	0.0352	0.7	4.4	1034.	0.0530	59.3	0.20
5	7.7	60.0	-0.4	29.0	0.0354	0.9	5.7	1004.	0.0339	70.3	0.20
6	3.4	60.0	0.0	29.1	0.0355	1.0	5.4	1051.	0.0322	70.0	0.20
7	3.4	60.0	0.9	29.4	0.0359	0.8	5.6	1032.	0.0320	70.2	0.20
8	7.7	60.0	1.6	29.5	0.0359	0.9	5.7	1041.	0.0312	70.3	0.20
9	7.7	60.0	9.0	19.6	0.0352	5.1	5.8	991.	0.0155	75.5	0.20
10	3.3	60.0	9.2	18.9	0.0353	5.1	5.7	1008.	0.0147	79.0	0.20
11	3.3	60.0	9.5	19.6	0.0353	4.7	5.3	1011.	0.0148	75.2	0.20
12	7.7	60.0	9.7	19.6	0.0343	5.0	5.7	1007.	0.0148	75.0	0.20
13	7.7	60.0	-2.0	81.5	0.0355	2.2	10.0	1030.	0.0836	39.8	0.20
14	3.4	60.0	-1.0	81.8	0.0352	2.0	10.9	1050.	0.0815	42.0	0.20
15	3.4	60.0	-0.2	81.8	0.0357	1.8	11.5	1037.	0.0818	43.7	0.20
16	7.7	60.0	0.5	81.6	0.0354	1.3	12.8	1029.	0.0816	45.1	0.20

RUN	TSKY (C)	HW "(W/SQM-C)"	UL	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	-25.9	8.7	4.48	0.95	64.3	60.7	55.8	59.4	0.0497
2	-24.8	8.0	4.40	0.95	59.8	61.2	55.8	54.4	0.0497
3	-24.5	8.7	4.48	0.95	63.9	61.0	56.2	59.1	0.0490
4	-24.0	8.4	4.45	0.95	59.3	61.1	56.1	54.3	0.0492
5	-24.5	9.1	4.36	0.95	70.3	69.5	66.7	67.5	0.0293
6	-24.0	9.5	4.40	0.95	70.0	70.1	67.5	67.5	0.0277
7	-22.7	8.7	4.33	0.95	70.2	70.4	67.6	67.4	0.0276
8	-21.8	9.1	4.36	0.95	70.3	70.6	68.0	67.7	0.0268
9	-11.5	25.1	4.68	0.94	75.5	76.0	75.9	75.5	0.0107
10	-11.3	25.1	4.66	0.94	79.0	76.5	76.4	78.9	0.0096
11	-10.8	23.6	4.65	0.94	75.2	76.4	76.3	75.1	0.0100
12	-10.6	24.7	4.66	0.94	75.0	76.3	76.4	75.0	0.0098
13	-26.7	14.1	5.14	0.94	39.8	41.4	37.9	36.3	0.0811
14	-25.3	13.3	5.09	0.94	42.0	42.9	39.2	38.3	0.0789
15	-24.2	12.5	5.03	0.94	43.7	43.3	39.1	39.5	0.0791
16	-23.3	10.6	4.87	0.94	45.1	44.7	39.2	39.7	0.0788

COLLECTOR TEST FACILITY,O CHAMBERLAIN

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	11.4	59.5	9.2	28.7	0.0398	2.2	15.0	1067.	0.0228	67.8	0.54
2	5.4	59.5	9.7	29.4	0.0370	3.1	11.8	1083.	0.0229	67.0	0.54
3	7.6	59.5	10.3	28.6	0.0350	3.6	13.8	1072.	0.0221	66.3	0.54
4	14.1	59.5	10.3	28.4	0.0383	3.1	12.7	1039.	0.0221	68.6	0.54
5	11.8	59.5	13.9	43.7	0.0359	1.3	7.4	1020.	0.0340	65.9	0.54
6	5.7	59.5	13.3	42.8	0.0361	0.9	6.8	1043.	0.0334	72.9	0.54
7	7.3	59.5	13.3	44.7	0.0366	0.9	7.0	1037.	0.0352	69.6	0.54
8	13.8	59.5	12.5	43.5	0.0358	1.8	7.8	1005.	0.0356	66.9	0.54
9	12.2	59.5	3.6	52.8	0.0347	1.3	8.0	1040.	0.0511	52.0	0.54
10	6.0	59.5	4.7	55.3	0.0344	4.0	7.7	1071.	0.0512	53.4	0.54
11	7.0	59.5	5.0	56.0	0.0342	5.4	8.1	1062.	0.0521	55.3	0.54
12	13.3	59.5	5.3	52.2	0.0335	5.4	8.6	1022.	0.0505	59.2	0.54
13	12.3	59.5	9.4	69.4	0.0319	1.3	7.2	1041.	0.0611	45.7	0.54
14	6.1	59.5	10.0	71.3	0.0321	3.6	6.9	1068.	0.0612	50.2	0.54
15	6.8	59.5	10.3	63.9	0.0333	4.9	7.3	1069.	0.0547	59.4	0.54
16	13.2	59.5	10.8	68.6	0.0314	4.5	7.4	1036.	0.0598	50.8	0.54

RUN	TSKY (C)	HW "(W/SQM-C)"	UL "(W/SQM-C)"	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	-11.3	14.1	4.61	0.93	67.8	71.8	72.3	68.3	0.0183
2	-10.6	17.5	4.75	0.93	67.0	71.4	72.3	67.9	0.0182
3	-9.7	19.4	4.79	0.93	66.3	71.5	72.9	67.7	0.0171
4	-9.7	17.5	4.72	0.93	68.6	71.8	72.7	69.5	0.0174
5	-4.7	10.6	4.55	0.93	65.9	67.8	66.7	64.8	0.0292
6	-5.5	9.1	4.42	0.93	72.9	68.8	67.2	71.3	0.0283
7	-5.5	9.1	4.44	0.93	69.6	68.0	66.2	67.8	0.0303
8	-6.7	12.5	4.67	0.93	66.9	66.5	65.9	66.3	0.0308
9	-19.0	10.6	4.68	0.93	52.0	59.4	57.1	49.7	0.0473
10	-17.5	20.9	5.23	0.92	53.4	56.3	57.1	54.3	0.0472
11	-17.1	26.2	5.38	0.92	55.3	55.0	56.7	57.0	0.0480
12	-16.7	26.2	5.32	0.92	59.2	56.2	57.9	60.9	0.0459
13	-11.0	10.6	4.78	0.93	45.7	54.2	51.4	42.9	0.0576
14	-10.1	19.4	5.30	0.92	50.2	50.9	51.5	50.8	0.0574
15	-9.7	24.3	5.38	0.92	59.4	54.0	55.5	61.0	0.0501
16	-9.0	22.8	5.38	0.92	50.8	51.1	52.4	52.2	0.0558

COLLECTOR TEST FACILITY,R CHAMBERLAIN

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	13.4	47.0	21.1	27.9	0.0349	4.0	14.0	990.	0.0116	77.4	0.00
2	14.4	47.0	20.9	28.1	0.0348	5.4	14.0	1024.	0.0113	74.2	0.00
3	15.4	47.0	21.5	28.3	0.0349	8.0	14.0	969.	0.0122	77.8	0.00
4	16.4	47.0	21.5	28.5	0.0347	7.2	14.0	952.	0.0126	78.2	0.00
5	9.8	35.0	9.3	61.0	0.0347	1.3	6.3	1052.	0.0528	61.0	0.00
6	9.7	35.0	8.8	61.0	0.0348	5.4	6.3	1050.	0.0534	60.9	0.00
7	9.7	35.0	9.3	61.0	0.0348	1.3	6.3	1053.	0.0528	60.7	0.00
8	9.8	35.0	10.0	61.2	0.0348	2.2	6.3	1060.	0.0519	60.3	0.00
9	9.8	35.0	19.3	39.6	0.0347	6.7	12.0	1026.	0.0243	74.0	0.00
10	9.8	35.0	19.8	39.6	0.0348	3.6	12.0	1023.	0.0239	74.2	0.00
11	9.3	35.0	20.3	39.9	0.0347	4.0	12.0	1020.	0.0237	73.8	0.00
12	9.4	35.0	20.8	39.6	0.0346	8.9	12.0	1020.	0.0229	74.4	0.00
13	2.8	32.0	17.3	81.2	0.0348	5.8	10.0	1061.	0.0632	50.3	0.00
14	2.9	32.0	17.6	81.5	0.0348	1.8	10.0	1071.	0.0626	50.8	0.00
15	2.8	32.0	17.1	81.5	0.0347	4.0	10.0	1068.	0.0632	49.6	0.00
16	3.2	32.0	18.1	81.5	0.0348	2.7	10.0	1069.	0.0623	51.3	0.00

RUN	TSKY (C)	HW "(W/SQM-C)"	UL "(W/SQM-C)"	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	5.5	20.9	4.67	0.95	77.4	77.6	77.7	77.5	0.0069
2	5.2	26.2	4.80	0.95	74.2	77.3	77.7	74.6	0.0070
3	6.0	36.1	4.87	0.95	77.8	77.1	77.7	78.4	0.0070
4	6.0	33.1	4.85	0.95	78.2	77.0	77.5	78.7	0.0074
5	-11.1	10.6	4.92	0.95	61.0	58.8	56.1	58.3	0.0491
6	-11.8	26.2	5.69	0.94	60.9	53.9	55.8	62.7	0.0497
7	-11.1	10.6	4.92	0.95	60.7	58.8	56.1	58.0	0.0491
8	-10.1	14.1	5.18	0.94	60.3	57.6	56.6	59.2	0.0483
9	2.9	31.2	5.30	0.94	74.0	70.4	71.5	75.2	0.0198
10	3.6	19.4	5.04	0.94	74.2	71.4	71.7	74.5	0.0194
11	4.3	20.9	5.08	0.94	73.8	71.3	71.8	74.3	0.0192
12	5.0	39.5	5.37	0.94	74.4	70.8	72.2	75.8	0.0184
13	0.1	27.7	5.93	0.94	50.3	46.7	49.9	53.5	0.0602
14	0.5	12.5	5.22	0.94	50.8	51.7	50.2	49.3	0.0597
15	-0.2	20.9	5.71	0.94	49.6	48.1	49.9	51.4	0.0603
16	1.2	16.0	5.46	0.94	51.3	50.3	50.4	51.4	0.0593

COLLECTOR TEST FACILITY,U CHAMBERLAIN

RUN	THETA (DEG)	SLOPE (DEG)	T,AMB (C)	T,IN (C)	MDOT (KG/S)	WIND (M/S)	DIFF (%)	INSOL (W/SQM)	XPARM (SQM-C/W)	EFFCY (%)	ETH GLY FRAC
1	10.6	43.0	21.4	32.7	0.0375	0.8	10.8	1062.	0.0159	78.6	0.40
2	6.8	43.0	21.1	32.6	0.0375	1.2	10.7	1073.	0.0160	78.9	0.40
3	3.5	43.0	21.2	32.6	0.0375	1.9	10.0	1077.	0.0160	78.9	0.40
4	7.3	43.0	22.9	32.7	0.0375	1.2	9.8	1066.	0.0144	79.1	0.40
5	12.4	43.0	19.8	57.1	0.0369	0.8	9.9	1062.	0.0393	68.6	0.40
6	8.8	43.0	20.9	57.2	0.0369	1.0	9.8	1071.	0.0384	69.6	0.40
7	5.0	43.0	22.4	57.3	0.0369	1.4	9.8	1066.	0.0373	70.0	0.40
8	9.2	43.0	23.2	57.3	0.0369	1.0	9.5	1057.	0.0370	69.9	0.40
9	12.6	43.0	18.2	75.3	0.0365	0.9	13.1	1025.	0.0599	59.6	0.40
10	9.1	43.0	18.3	75.4	0.0365	1.0	13.3	1033.	0.0594	59.6	0.40
11	6.4	43.0	19.8	75.3	0.0365	1.9	12.5	1040.	0.0574	59.7	0.40
12	9.5	43.0	20.9	75.4	0.0365	1.3	12.1	1029.	0.0569	59.3	0.40
13	11.7	43.0	18.0	94.9	0.0360	0.8	10.5	1047.	0.0768	51.0	0.40
14	8.7	43.0	18.8	94.9	0.0360	1.1	9.9	1055.	0.0756	51.8	0.40
15	6.7	43.0	20.8	94.8	0.0360	0.8	9.0	1055.	0.0736	52.4	0.40
16	9.0	43.0	20.9	94.8	0.0360	1.4	8.6	1055.	0.0734	52.3	0.40

RUN	TSKY (C)	HW "(W/SQM-C)"	UL	FR	EFFICY (EXP)	EFFICY (THE)	EFFICY (STD)	EFFICY (COR)	PARM (EXP)
1	5.9	8.7	4.36	0.94	78.6	76.4	76.0	78.2	0.0106
2	5.5	10.3	4.48	0.94	78.9	76.1	75.9	78.7	0.0107
3	5.6	12.9	4.63	0.94	78.9	75.8	76.0	79.1	0.0106
4	8.0	10.3	4.46	0.94	79.1	76.8	76.7	78.9	0.0092
5	3.6	8.7	4.60	0.94	68.6	65.6	63.6	66.7	0.0351
6	5.2	9.5	4.67	0.94	69.6	65.8	64.3	68.1	0.0339
7	7.3	11.0	4.80	0.94	70.0	65.7	64.9	69.2	0.0327
8	8.5	9.5	4.66	0.94	69.9	66.6	65.2	68.5	0.0323
9	1.4	9.1	4.78	0.94	59.6	55.4	52.5	56.6	0.0557
10	1.5	9.5	4.83	0.94	59.6	55.4	52.7	56.9	0.0553
11	3.6	12.9	5.12	0.93	59.7	54.4	53.8	59.1	0.0534
12	5.2	10.6	4.93	0.93	59.3	55.8	54.0	57.5	0.0530
13	1.1	8.7	4.86	0.94	51.0	47.2	42.4	46.2	0.0734
14	2.2	9.9	5.00	0.93	51.8	46.7	43.1	48.2	0.0721
15	5.0	8.7	4.86	0.94	52.4	48.8	44.3	47.9	0.0701
16	5.2	11.0	5.11	0.93	52.3	46.9	44.3	49.7	0.0700

Analytical Relationships Used in the Collector Model for Analyzing the Effect of Environmental Conditions

NOMENCLATURE

A_c = net collector area

A_e = edge area

c_p = specific heat

D = outside diameter

D_e = hydraulic diameter

F = fin efficiency

F' = collector efficiency factor

F_R = flow factor

G = transfer fluid mass flow per unit collector area

h = film conductance

I = total solar radiation measured in the collector plane

k = thermal conductivity

K = length extinction coefficient

L = collector length, thickness

m = parameter (equation 34)

n = index of refraction

n_t = no. flow tubes

Nu = Nusselt No.

P_i = perimeter around fluid passageway

Pr = Prandtl No.

$\dot{Q}_u$ = useful energy

Ra = Raleigh No.

Re = Reynolds No., based on D_e

T = temperature

U = thermal conductance

V_w = wind speed

W = distance between flow tubes

α = absorptance

ε = emittance

η = efficiency, diffuse fraction

θ, θ_2 = angle between surface normal and beam radiation

ρ = reflectance

σ = Stefan-Boltzmann Constant

τ = transmittance

Subscripts

a air, ambient

b back side, beam

c, c1, c2 cover, no. 1 = inside

ca cover to ambient

d diffuse

e effective, edge

f transfer fluid

fi fluid inlet

i long wavelength diffuse, back insulation

j cover no.

L overall loss

o fluid-to-ambient loss

p absorber plate

pc plate-to-cover 1

m mean

r radiation

s solar wavelength specular property, sky

T top loss

α considering absorptance only

12 cover 1 to cover 2

$||,\perp$ two components of polarization

The collector efficiency is given by

$$\eta = \frac{\dot{Q}_u}{I\ A_c} \times 100\% \tag{1}$$

where I is the total solar radiation on the (outer) surface of the cover as measured by a pyranometer in the same plane. The useful heat transfer is given by

$$\dot{Q}_u = A_c F_R\ ((\tau\alpha)_e\ I - U_L(T_{fi} - T_a)) \tag{2}$$

A summary of the relationships which lead to expressions for U_L, $(\tau\alpha)_e$ and F_R follow. The developments are essentially from reference [6]. Reference [13] was used in developing the expressions for optical properties. Heat transfer correlations for internal flow and natural convection are from references [19] and [20] respectively. Expressions for the properties of air were taken from reference [21].

The expressions are listed for analyzing the two-cover collector. A brief discussion of the changes required to analyze the single cover system follows the list of equations.

The expression for the loss coefficient is developed from

$$U_b = \frac{k_i}{L_i} \tag{3}$$

$$U_e = \frac{k_e}{L_e}\frac{A_e}{A_c} \tag{4}$$

$$h_w = \{5.7 + 3.8[V_w, m/s]\}\ W/(m^2 \cdot {}^\circ C) \tag{5}$$

$$T_s = [0.0552\ (T_a/{}^\circ K)^{1.5}]\,{}^\circ K \tag{6}$$

$$h_{rpc} = \frac{\sigma[T_{pm}^2 + T_{c1}^2]\ [T_{pm} + T_{c1}]}{1/\varepsilon_p + 1/\varepsilon_{c1} - 1} \tag{7}$$

$$h_{pc} = Nu(Ra)\ [k_a/L_{pc}] \tag{8}$$

$$U_{pc} = h_{rpc} + h_{pc} \tag{9}$$

$$h_{r12} = \frac{\sigma[T_{c1}^2 + T_{c2}^2]\ [T_{c1} + T_{c2}]}{1/\varepsilon_{c1} + 1/\varepsilon_{c2} - 1} \tag{10}$$

$$h_{12} = Nu(Ra)\ [k_a/L_{12}] \tag{11}$$

$$U_{12} = h_{r12} + h_{12} \tag{12}$$

$$h_{rca} = \varepsilon_{c2}\sigma[T_{c2}^4 - T_s^4]/[T_{c2} - T_a] \tag{13}$$

$$U_{ca} = h_w + h_{rca} \tag{14}$$

$$U_T = [1/U_{pc} + 1/U_{12} + 1/U_{ca}]^{-1} \tag{15}$$

$$T_{c1} = T_{pm} - [U_T/U_{pc}]\ [T_{pm} - T_a] \tag{16}$$

$$T_{c2} = T_{pm} - U_T[1/U_{pc} + 1/U_{12}]\ [T_{pm} - T_a] \tag{17}$$

Finally

$$U_L = U_b + U_e + U_T + \tau_{i1}\tau_{i2}\varepsilon_p\sigma[T^4_{pm} - T^4_s]/[T_{pm} - T_a] \quad (18)$$

The effective transmittance-absorptance development is

$$\theta_{2,j} = \arc\sin(\sin(\theta)/n_j) \; ; \; j = 1,2 \quad (19)$$

$$\rho_{||,j} = \frac{\sin^2(\theta_2 - \theta)}{\sin^2(\theta_2 + \theta)} \quad (20)$$

$$\rho_{\perp,j} = \frac{\tan^2(\theta_2 - \theta)}{\tan^2(\theta_2 + \theta)} \quad (21)$$

$$\tau_{||,j} = [1 - \rho_{||,j}]^2/[1 - \pi^2_{\alpha s,j}\,\rho^2_{||,j}] \quad (22)$$

$$\tau_{\perp,j} = [1 - \rho_{\perp,j}]^2/[1 - \tau^2_{\alpha_s,j}\,\rho^2_{\perp,j}] \quad (23)$$

$$\tau_{\alpha s,j} = \exp(-L_{c,j}K_j/\cos\theta_2) \quad (24)$$

$$\tau_{s,j} = \tau_{as,j}[\tau_{||,j} + \tau_{|,j}]/2 \quad (25)$$

$$\rho_{||c,j} = \frac{\rho_{||,j}\{1 + \tau^2_{\alpha s,j}[1 - 2\rho_{||,j}]\}}{1 - \tau^2_{\alpha s,j}\rho^2_{||,j}} \quad (26)$$

$$\rho_{\perp c,j} = \frac{\rho_{\perp,j}\{1 + \tau^2_{\alpha s,j}[1 - 2\rho_{\perp,j}]\}}{1 - \tau^2_{\alpha s,j}\,\rho^2_{\perp,j}} \quad (27)$$

$$\rho_{c,j} = [\rho_{||c,j} + \rho_{\perp c,j}]/2 \quad (28)$$

$$\tau_{s12} = \tau_{s1}\,\tau_{s2}/[1 - \rho_{c1}\,\rho_{c2}] \quad (29)$$

$$\rho_{c12} = \rho_{c1} + \rho_{c2}\tau^2_{s1}/[1 - \rho_{c1}\rho_{c2}] \quad (30)$$

$$\tau_{sd} = \int_0^{\pi/2} \tau_s(\theta)\sin(2\theta)\,d\theta \quad (31)$$

where $\tau_s(\theta)$ is given by equation (25) or (29) for 1 or 2 covers, respectively.

$$(\tau\alpha) = \frac{\alpha_p \{[1 - \eta_d] \tau_{s12} + \eta_d \tau_{sd,12}\}}{1 - [1 - \alpha_p]\rho_{c12}(60°)} \qquad (32)$$

Finally,

$$(\tau\alpha)_e = (\tau\alpha) + \tau_{s2}[1 - \tau_{\alpha s,1}] [1 - U_{pa}/U_{pc}] + [1 - \tau_{\alpha s,2}]\{1 - U_{pa} [1/U_{pc} + 1/U_{12}]\} \qquad (33)$$

The expression for F_R is developed from

$$m = (U_L/[k_p L_p])^{1/2} \qquad (34)$$

$$F = \sinh (m[W-D]/2)/\{\cosh (m[W-D]/2)m[W-D]/2\} \qquad (35)$$

$$Nu_f(RePrD_e/L) = 3.66 + \frac{0.0668 [RePrD_e/L]}{1 + 0.04 (RePrD_e/L)^{2/3}}$$

$$h_f = Nu_f[k_f/D_e] \qquad (37)$$

$$U_o = \{W[1/\{U_L[D + F(W - D)]\} + 1/[P_i h_f]\}^{-1} \qquad (38)$$

$$F' = U_o/U_L \qquad (39)$$

$$F_R = [G c_p/U_L] \{1 - \exp (-F'U_L/[G c_p])\} \qquad (40)$$

Since the calculations proceed in an iterative fashion, the following expressions are used to converge the plate and fluid temperatures.

$$T_{fm} = T_{fi} + \dot{Q}_u/\{A_c U_L F_R[1 - F_R/F']\} \qquad (41)$$

$$T_{pm} = T_{fm} + \dot{Q}_u P_i h_f/[L n_t] \qquad (42)$$

For collector No. 2 with a single cover, equations (10-12) and (17) were not used. The subscript "c2" in equation (13) was replaced with "c1", $1/U_{12}$ was deleted in equation (15) and τ_{i2} was deleted from equation (18). In a similar fashion, j = 1 in the $(\tau\alpha)_e$ development; equations (29) and (30) were not used; the 2's were deleted from the subscripts in equation (32); the last term and τ_{s2} were deleted from equation (3); and, finally, the fin efficiency, equation (35), was essentially unity.

The order of progression of computation using a digital computer for this model is described. The environmental conditions, operating conditions, collector dimensions, heat transfer properties, and other quantities shown in Table C1 must be specified to calculate efficiency. The computational procedure uses several iterative loops to handle the nonlinear dependence of U_L on temperature. Equations (3-6) and (19-32) are solved. Equation (31) is integrated numerically using a trapezoidal scheme. For a specified inlet temperature, a trial value several degrees higher is assumed for the mean plate temperature. The cover temperatures are calculated from equations (16) and (17) for the assumed mean plate temperature until the former converge within 0.5 °C. A top-loss coefficient is determined from equation (15) for the trial plate temperature. Equations (18) and (33-35) are next solved. The mean fluid temperature is assumed initially as the plate temperature to determine fluid properties and the convection heat transfer coefficient using equations (36) and (37). The collector efficiency factor and heat removal factor are calculated from equations (38-40). The useful heat transfer is next determined from equation (2) and subsequently used in equation (41) to check the assumed mean fluid temperatures. The calculations are repeated using the updated fluid temperatures until convergence within 0.5 °C is obtained. The mean plate temperature is then calculated from equation (42) and compared with the assumed value. The calculations starting with equation (16) are repeated until the plate mean temperature converges to within 0.5 °C. Finally, the collector efficiency is determined from equation (1).

The analytical model and computer code were verified by checking final results with a desk calculator and by comparison with other theoretical results in the literature. In particular, the result for the theoretical model agrees with those shown in references [2] and [22].

The required dimensions were taken from the collector manufacturer's literature [23, 24] and from the information in Table 1. The heat transfer properties for the collector materials were generally those provided by the manufacturers or from a handbook [25]. The dimensions and heat transfer properties used for both collectors No. 1 and 2 are shown in Table C1. Since a considerable amount of uncertainty was associated with the effective value of the edge-loss coefficient, it was selected primarily on the basis of giving the best least squares fit of theoretical to experimentally determined efficiencies. The experimental results also influenced the selection of the "extinction coefficient" of the cover materials when used with the index of refraction shown. With these two parameters specified, equations (19-29) can be used to calculate transmittance values in terms of the beam incident angle.

Table C1. Summary of Environmental and Operating Conditions and Collector Properties for the Theoretical Performance Model

Environmental and Operating Conditions: "Standard" Values

T_a = 20°C	U = 1000 W/m^2	V_w = 3 m/s
η_d = 0.15	G = 0.02 kg/(s·m^2)	θ = 15°
S = 45°	Ethylene Glycol Concentration = 0.0	

Dimensions and Heat Transfer Properties

A. PPG Collector; A_c = 1.602 m^2

L = 0.841 m	n_t = 13	D = 1.27 cm
D_e = 1.2 cm	P_i = 1.5 cm	L_p = 1.524 mm
k_p = 221 W/(m·°C)	ε_p = 0.92	α_p = 0.95
L_i = 5.35 cm	k_i = 0.045 W/(m·°C)	U_e = 1.50 W/(m^2·°C)
L_{pc} = 0.953 cm	ε_c = 0.85	τ_{ic} = 0.02
n = 1.518	KL_c = 0.04	L_{12} = 0.953 cm

B. CMC Collector; A_c = 1.789 m^2

L = 0.860 m	n_t = 19	D = 4.07 cm
D_e = 0.5 cm	P_i = 8.5 cm	L_p = 0.911 mm
k_p = 47.6 W/(m·°C)	ε_p = 0.12	α_p = 0.96
L_i = 7.62 cm	k_i = 0.045 W/(m·°C)	U_e = 0.90 W/(m^2·°C)
L_{pc} = 1.9 cm	ε = 0.88	τ_{ic} = 0.02
n = 1.518	KL_c = 0.035	

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

A round robin test program was conducted at 21 United States test facilities, using a common test procedure, to determine the intercomparability of thermal performance data pertaining to two liquid-heating flat-plate solar collectors.

The statistical analysis of the data revealed a relatively large spread in the measured values of collector efficiency. Data from approximately half the facilities were then selected for detailed analysis. A collector analytical model was used to show that less than one-third of the mean-square distance could be attributed to different environmental conditions from facility to facility. It was found that the data showed less scatter for one of the two collectors than for the other. In general, the data were consistent for any single facility; most of the scatter was therefore attributed to systematic uncertainties from facility to facility. When the data from six participants reportedly adhering to the requirements of ASHRAE Standard 93-77 were analyzed, the scatter was found to be within normal limits expected for the test procedure.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*)

Measurement; modelling; solar; standards; testing.

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